University of Alberta

Pulp Mill Effluent as a Supplemental Water Source for Irrigation

By

Shane Joseph Patterson ©

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ABSTRACT

Agroforestry systems for wastewater irrigation have been underutilized in Canada and could be 'greener' alternatives for allow industries and communities to effluent discharge into water bodies. Effluents are a valuable resource of both water and nutrients. When combined these systems can be advantageous in sub-humid climates at more northern latitudes where research into incorporating effluents as supplemental sources of irrigation water has been limited.

Over five years, three growth chamber studies and one field study were conducted to evaluate the potential use of Kraft pulp mill effluents as sources of irrigation water. These studies evaluated the effects irrigating with water, effluents from a Kraft pulp mill [a final effluent and a waste activated sludge] and a municipality and various combinations of distilled water and Kraft pulp mill effluents would have on selected soil chemical properties and the growth and nutrient uptake of hybrid poplar (*Populus deltoides* x *P. petrowskyana*), reed canarygrass (*Phalaris arundinacea* L.), timothy (*Phleum pratense* L.), alsike clover (*Trifolium hybridum* L.), and winter wheat (*Triticum aestivum* L.).

Pulp mill effluents consistently resulted in significant increases in soluble SO_4^{2-}, Na^+, and Cl^- in the soil while diluting the effluents reduced these increases. Electrical conductivity of saturated paste extracts (ECe) and sodium adsorption ratio (SAR) increased with pulp mill effluents compared to tap water (TPW) and municipal effluent (ME) but diluted treatments remained significantly greater than control treatments. Only when soils were amended with gypsum did solution SAR of soils irrigated with effluents decrease, due to additional Ca, compared to control soils. Wheat grown on wood ash-amended soils irrigated with effluents resulted in significant increases in biomass. Increasing the application rate significantly increased biomass for both crops, but the Kraft pulp mill effluent (KPME) treatment significantly decreased leaf area of the hybrid poplar (HYBP). Effluent/distilled water combinations (COMB) resulted in heights, biomasses, and leaf areas that were greater than those for KPME and were comparable to those for DW.

Results indicate dilutions and precipitation reduced ion accumulations within the rooting zone. Soil salt loading must be considered when determining application rates of effluents. However, more research is required for the management and timing of applications as effluent applications are likely required only during dry periods.

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LIST OF ABBREVIATIONS AND UNITS

AB	Alberta
AES	Atomic Emission Spectroscopy
AAFRD	Alberta Agriculture, Food, and Rural Development
Al	Aluminum
Al–Pac	Alberta-Pacific Forest Industries Inc.
As	Arsenic
(aq)	Aqueous, or in solution or liquid state
B_{HWS}	Hot Water Soluble Boron
CCME	Canadian Council of Ministers for the Environment
Ca	Calcium
$CaCO_3$	Calcium carbonate
CO_2	Carbon dioxide
CO_3	Carbonate
Cd	Cadmium
Cl	Chloride
Cr	Chromium
COMB	Combination Treatments: Irrigation treatments which involved combination of: Distilled Water (DW), Kraft Pulp Mill Effluent (KPME), or Waste Activated Sludge (WAS)
Cu	Copper
CEC	Cation exchange capacity
DW	Distilled Water
EC	Electrical Conductivity
ECe	Electrical Conductivity of saturated paste extracts
ECw	Electrical Conductivity of irrigation waters or irrigation sources (IS)
FC	Field Capacity
Fe	Iron
g	gram
(g)	Gas, in gaseous state
ha	hectare (10, 000 m^2)
H.EGL	Humic Eluviated Gleysols
HCO_3	Bicarbonate
Hg	Mercury

HYBP	Hybrid Poplar: *Populus deltoides x P. petrowskyana* L. **Note there are numerous *Populus* hybrid this was the hybrid selected for these studies
ICP	Inductively Coupled Plasma
IS	Irrigation Source: In this study consists of the Tap Water (TPW), Distilled Water (DW), Municipal Effluent (ME), Kraft Pulp Mill Effluent (KPME), or Waste Activated Sludge (WAS)
kPa	kilopascal
K	Potassium
kg	kilogram
L	litre
LA	leaf area
KPME	Kraft Pulp Mill Effluent: Final effluent produced by Alberta-Pacific Forest Industries, which is discharged after treatment to the Athabasca River
ME	Municipal Effluent: Final effluent produced by a small community near Al-Pac, which is discharged to a nearby lake
Mn	Manganese
m	meter
m^3	cubic meter
Mg	Magnesium
mg	milligram
mg kg^{-1}	milligram per kilogram
mg L^{-1}	milligram per litre
mL	millilitre
N	Nitrogen
Na	Sodium
NE	Northeast
NW	Northwest
OES	Optical Emission Spectroscopy
O.GL	Orthic Gray Luvisol
PAW	Plant Available Water – Difference between water content at Field Capacity (FC) and water content at wilting point (WP)
Pb	Lead
ppm	Parts per million
S	Sulphur
(s)	Solid form
RCG	Reed canarygrass: *Phalaris arundinacea* L.
Se	Selenium

SE	Southeast
SO_4	Sulphate
SW	Southwest
SAR	Sodium Adsorption Ratio
SAR_{adj}	Sodium Adsorption Ratio: SAR adjusted according to Ayers and Westcot (1994) to account for HCO_3^- effects on Ca^{2+} and Mg^{2+} in the soil and solution
t	metric tonne (1 tonne = 1000 kg)
$t\ ha^{-1}$	tonne per hectare
TDS	Total Dissolved Solids
TSW	Total Soil Water
TSW	Total Soil Water of 0-40 cm depth increment
USA	United States of America
VMC	Volumetric Moisture Content
WAS	Waste Activated Sludge: Secondary effluent produced by Alberta-Pacific Forest Industries
WP	Wilting Point
Zn	Zinc

1. *Potential Use of Pulp Mill Effluent as Supplemental Sources of Irrigation Water*

Agroforestry and irrigation are not new concepts in Alberta or internationally. Traditionally trees have been used as windbreaks and shelterbelts throughout the Canadian Prairie to provide protection and minimize erosion. Irrigation has been practiced since the late 1800s in southern Alberta (SMRID 2007), and historically back to 6000 BC in ancient Egypt and Mesopotamia (Hillel 1998). Through irrigated agricultural or agroforestry systems, industries and communities can seek 'greener' alternatives to effluent discharge into water bodies. Effluents can be viewed as a valued resource, rather than as a troublesome and useless by-product (waste). Numerous studies have shown the success of effluent irrigated plantations of eucalyptus, pine (Stewart and Flinn 1984; Myers et al. 1996) and poplar (Carlson 1992). Through agroforestry systems, crop combinations can be tailored to maximize water and nutrient use throughout the growing season, to minimize environmental impacts, and to maximize economic returns (Rosenqvist et al. 1997; Sharma and Ashwath 2006). These systems can be advantageous in sub-humid climates at more northern latitudes where research into incorporating effluents as supplemental sources of irrigation water has been limited.

Traditionally, treated effluents have been directly discharged into surface water bodies, which may also serve as a potable water source. A continuing requirement for high quality water for consumption and acceptable locations for disposal places great strain on these water resources as municipalities and industries have a direct impact on water quality through the discharge of treated, and in some cases untreated, effluent. As a result, alternatives to direct discharge of treated effluents to water bodies are actively sought. As urban areas, agriculture and resources based industries continue to expand, so does the competition for potable sources of water. Water scarcity is a growing issue in arid countries; and even in regions of Alberta upwards of 71% of the consumptive use of surface water is for irrigation, while only 0.6% of Alberta's groundwater is used for irrigation (Alberta Government 2002). The report states industry in Alberta accounts for 14.8 and 52.8% of the surface water and groundwater, respectively. Alberta contains 60% of the 10,000 km^2 of irrigated cropland that is located within Canada (Environment Canada 2004). Irrigation technology has changed dramatically allowing for greater water storage, greater distance of transport, and better control over application.

1.1 EFFLUENT QUALITY

Recently there has been a focus on the reuse of lower quality waters, including drainage water and effluents, as supplemental sources in irrigation. There are benefits and risks associated with the use of these water sources when considering their inclusion within irrigation programs (Toze 2006). Soil salinity and sodicity, unless carefully managed, can detrimentally affect site productivity through changes in osmotic potentials, affect plant water uptake and soil fertility (Letey 1993; Volkmar et al. 1998). Tolerances of selected crops to exchangeable sodium and salinity are shown in Table 8.1 and Table 8.2 (Appendix – A). Quality becomes the main issue when considering the use of these water sources within irrigation programs, whether its use is providing the only source of water or the effluent is supplementing better quality water. Effluents contain ions that over time may accumulate within the rooting zone, thus potentially reducing plant productivity. Table 9.1 and Table 9.2 (Appendix – B) show some of the guidelines and parameters which should be considered when considering effluents as an irrigation source.

Although effluents can undergo various stages of water treatment (e.g., primary, secondary, or tertiary), they still contain varying and valuable concentrations of nutrients [e.g., nitrogen (N) and phosphorus (P)], dissolved ions [e.g., chloride (Cl^-) and sodium (Na^+)], and trace elements [e.g., boron (B)]. As a result, discharging effluents can lead to environmental concerns over water quality and induce issues like eutrophication (Daniel et al. 1998). Effluent quality is highly dependent on factors such as the size of town or municipality, type of industry (e.g., forestry versus food processing), type of industrial process (e.g., Kraft pulping versus chemical/thermal/mechanical pulping (CTMP)), kind of treatment (e.g., primary, secondary, tertiary), focus of treatment (e.g., nutrient versus biological), and cost of treatment. Their use, however, requires careful consideration of these factors in proper management, since each site to be irrigated provides unique site-specific challenges (i.e., local soils, vegetation, meteorological conditions, etc.). These factors have direct influences on if, when, and how a site should be irrigated. Depending on the quality, effluents can provide a source of water and nutrients but their use can pose environmental problems in water and soils if not properly managed (Hillel 1998). This becomes critical since over-irrigation can raise water tables and lead to water quality issues in both ground and surface water. Thus, the use of effluents for irrigation needs to consider carefully the long-term implications along with the short-term gains.

Municipal and agricultural effluents have been studied extensively, but other industries like pulp and paper mills discharge vast amounts of effluents, which have potential for irrigation programs. For example, the Kraft mill providing the effluent used in this study discharges upwards of 70,000 m^3 of final treated effluent (KPME) into the Athabasca River on a daily basis. The KPME lower concentrations of nutrients like N and P and has higher concentrations of dissolved ions like chloride (Cl^-), sodium (Na^+), and sulphate (SO_4^{2-}) than municipal effluents (ME). The concentrations of each depend on the stage and level of treatment. Kraft pulping requires the use of Na^+ and SO_4^{2-} compounds during the digestion of hard and softwood chips into pulp which then undergoes bleaching, typically with Cl^- compounds like chlorine dioxide (ClO_2) (Smook 1989). Other partially treated effluents, like waste activated sludge (WAS) for example, have not undergone any settling and can contain higher N, P, and organic matter concentrations than does KPME. Municipal effluents also contain SO_4^{2-} and Na^+ used for water treatment and Cl^- sometimes used during the disinfection of water and effluents. The high concentration of sodium within municipal effluents is the result of the day-to-day use of soaps and detergents containing Na^+, such as sodium borate. Such products were used to replace sodium phosphate that for many years had been one of the primary ingredients in detergents used for daily cleaning, but their accumulation within the environment lead to excessive algal growth and lake eutrophication (Schindler 1974).

1.2 SUPPLEMENTAL IRRIGATION

Research into effluent irrigation has been studied extensively in arid regions where water is scarce (Qadir et al. 2003; Fuchs 2007), but limited research has been conducted in sub-humid climates. As such, crop water relations are fairly well understood under monoculture or monocropping (i.e., single cropping) systems in arid environments. However, similar water relations / productivity questions have not yet been determined and need to be posed for sub-humid regions. The suitability of different forages, trees, or crop combinations for effluent irrigation also needs to be determined in these regions. Precipitation in these regions can provide a majority of the water required during the growing season. However, during certain periods crop water use may exceed precipitation resulting in crop water deficits. Supplemental irrigation with effluents combined with precipitation can be utilized to manage leaching of dissolved salts from the root zone and provide a large portion of the crop water requirements. In sub-humid to semi-arid environments, supplemental irrigation strategies could be adopted for effluent irrigation with excess irrigation water or annual precipitation being relied on to flush ions from the root zone. The degree to which precipitation promotes leaching depends on both soil and meteorological conditions, and thus varies from year to year.

There may be opportunities to utilize and combine effluents from a number of industries or municipalities. Municipal effluent and effluents from dairies and rendering plants have been used to irrigate various forages (e.g., reed canarygrass, timothy, rye, corn, etc.) (Tesar and Knezek 1982; Bole and Gould 1985; Roygard et al. 2001). Pulp and paper mills produce nutrient rich secondary effluents that contain concentrations of N (2-5%) and P (1-4%) comparable to municipal effluents. Effluents have been used in arid areas as replacements or supplements to better quality water sources within irrigation programs (Shalhevet 1994; Qadir et al. 2003). Effluents could be used for this supplemental purpose in sub-humid areas as well and when properly managed could address nutrient management, crop diversification, carbon sequestration, and water quality.

1.3 SOIL AMENDMENTS TO AMELIORATE SODIUM RELATED ISSUES

Salt concentrations in effluents are one of the primary concerns and can become an environmental issue with over application when considering the use of pulp mill effluents for irrigation. Salt related issues arise in plant-soil water relations as they are not required in large amounts by the plant and can cause drought-like conditions by reducing osmotic potentials within the soil solution making water uptake more difficult for the plant. Tolerances of selected crops to exchangeable sodium and salinity are shown in Table 8.1 and Table 8.2. Dissolved salts such as Na^+, Cl^-, and SO_4^{2-} when applied during irrigation can precipitate, accumulate in the soil profile in or below the rootzone, and subsequently reduce crop productivity if not properly managed. While Cl^- and SO_4^{2-} can be managed through over-irrigation to leach these ions out of the root zone, they could, however overtime lead to groundwater issues depending on local water use requirements. Sodium requires a separate management strategy such as the application of amendments like gypsum, wood ash, or lime that contain Ca. Elemental S could also be applied to create zones of acidity, solubilizing Ca already present in the soil. The addition of Ca^{2+} to the soil displaces Na^+ off cation exchange sites allowing Na^+, along with Cl^- or SO_4^{2-} to be leached below the rooting zone where it may accumulate depending on soil textures and cation exchange capacity at depth (Howe and Wagner 1999). Cropping systems, like agroforestry, or afforestation can also aid in this process as the decomposition of organic matter and production of CO_2. The resulting increase in CO_2 within the soil solution would form carbonic acid (H_2CO_3; Equation 1.1) lowering solution pH solubilizing Ca^{2+} contained as $CaCO_3$ (Equation 1.2) within the profile to reduce the deleterious effects caused by Na^+ within the soil profile (Mishra et al. 2004).

Equation 1.1: $\mathbf{CO_{2(g)} + H_2O_{(l)} \leftarrow\rightarrow H_2CO_{3(aq)}}$

Equation 1.2: $\mathbf{H_2CO_{3(aq)} + CaCO_{3(s)} \leftarrow\rightarrow Ca^{2+} + 2HCO_3^-{}_{(aq)}}$

1.4 CROP SELECTION

Crop selection can be tailored to suit specific climatic, environmental, economic, or social conditions. Hybrid poplar and perennial forage crops are ideally suited for sub-humid areas, as they are known for their high water use because of larger biomass and extensive root systems and, in the case of forages, season-long green leaf area promoting evapotranspiration. Rapidly growing plant species and/or those with extensive root systems are typically the highest water users. Effluent irrigation projects could be utilized for irrigating non-food related crops such as trees, forages, grains, and oilseeds specifically grown for cellulose or biofuel production. Species used in the trials are listed below:

Alsike clover (*Trifolium hybridium* L. cv. Aurora) is a short-lived perennial legume used for hay and forage production in grass mixtures (i.e., timothy + alsike clover; reed canarygrass + alsike clover) that is more tolerant to colder and wetter climates and deals with less fertile soils better than other clovers (Pederson 1995). Alsike clover is tolerant of acid and alkaline soils (AAFRD 2001a), but considered to have low tolerance to salinity (Wentz 2001).

Reed canarygrass (*Phalaris arundinacea* L. cv. Vantage) is a tall-growing, coarse, sod-forming, cool season perennial that is adapted to wet soils (Sheaffer and Marten 1995). It is more adapted to diverse climatic conditions than most alternative perennial grasses. It has moderate tolerance to salinity and alkalinity and has persistence under moisture deficits equal, or superior, to other cool season grasses (AAFRD 2001b; Sheaffer and Marten 1995). Newer varieties have improved palatability for livestock. Reed canarygrass has been used in municipal effluent irrigation studies due to its high nutrient and water utilization potential (Linden et al. 1981). Reed canarygrass is considered to have a moderate tolerance to salinity (Wentz 2001). For example, reed canarygrass (RCG) varieties with lower alkaloid contents would be appropriate as RCG is adapted to local climate and soil conditions and could be sold in a broad range of these markets (i.e., feed, biomass, bioproducts, etc.). Reed canarygrass, for example, has been studied for its suitability for pulp and paper production (Fennell and Nilsson 2004) and for use in biogas production (Geber 2002).

Timothy (*Phleum pratense* L. cv. Climax) is a cool season perennial bunchgrass, well adapted to high elevations but is not very competitive (McElroy and Kunelius 1995). It is shallow-rooted and is not drought tolerant (AAFRD 2001c), but very responsive to fertilization. Timothy is considered to have low tolerance to salinity and alkalinity (Wentz 2001). Timothy is easy to establish and manage for hay, is a well-known horse hay crop, and is used for export to the Japanese market as a fiber replacement for rice straw in daily rations.

Winter Wheat (*Triticum aestivum* L. cv. Osprey) is a cereal crop seeded in early fall that during the next year overwinters as a seedling, allowing wheat to take advantage of a long growing season (Fowler 2002). Winter wheat has a high tolerance (i.e., < 8 dS m^{-1}) of salinity and moderately tolerant to acidic soils and can provide some soil erosion protection. This crop has an advantage over spring weeds due to fall establishment and matures quickly, allowing earlier harvesting giving it a market advantage to other wheat varieties.

Hybrid Poplar *(Populus deltoides x P. petrowskyana* L. cv. Walker) Hybrid and native poplars are becoming important for production of pulp and various manufactured wood products. Hybrid poplar exhibit very high growth rates and are short lived under arid conditions (i.e., 20 to 25 yrs) but may survive 50 to 60 yrs under moist conditions. Poplars produce a shallow root system (< 1 m) and may spread up to 20 m from their base, resulting in great uptake of nutrients and water. *Populus* responds positively to the application of municipal and industrial effluents (Carlson 1992). Poplar is considered to have a moderate tolerance to salinity (Wentz 2001). Walker poplar is one of the primary hybrid poplar clones currently being used in the Al-Pac poplar farm program.

Hybrid poplar monocrops do not have high water use in the years immediately after planting and at some points during the growing season. Intercropping with forage species might result in more uniform water use throughout the season. Higher plant water use would facilitate higher effluent application rates, increasing water availability to plants, resulting in higher plant productivity, which cyclically leads to higher plant water use. Furthermore, little is known about how intercropping *Populus* with forages affects overall water use, competitive interactions, and productivity. Intercropping hybrid poplar with select forages can further influence these interactions, possibly allowing for maximized water and nutrient uses. This reduces the potential for groundwater contamination through more efficient water use especially during the establishment stage for the poplars. At early stages of plantation development, even early on in the growing season, intercropped forages could utilize water which otherwise would be lost through leaching and / or surface runoff. Responses to effluent irrigation are inherently different between agricultural and forest crops and interactions among these crops are presently not well understood. As such, a key uncertainty remains as to the effects of applying industrial effluent to intercropped poplar plantations.

1.5 RESEARCH NEEDS

Only a few crop irrigation studies over the last two decades have been conducted using pulp or paper mill effluents. These studies have included: a flood irrigation study in USA (Hansen et al. 1980); a greenhouse study incorporating Ca amendments (e.g., gypsum) in conjunction with papermill effluent in USA (Howe and Wagner 1996); a follow up study in Arizona 15 years after irrigation with pulpmill effluent had been stopped in USA (Howe and Wagner 1999); a study of groundwater quality focusing on heavy metals (Cd, Cr, Cu, Pb, and Zn) and organochlorine residues where soils were irrigated with papermill effluent in India (Rekha et al. 2004); and a lysimeter study using thermo-mechanical pulp mill effluent as an irrigation water source in New Zealand (Wang et al. 2005).

None of these evaluated the use of mill effluents under a sub-humid climate. Effluent irrigation studies, in sub-humid areas, is of interest as little information is available about the effects on plant growth, nutrient uptake, and soil chemical properties. Effluent chemistry plays an integral role in determining the long term sustainability of irrigation projects involving effluents. Specifically, effluent sodium adsorption ratio (SAR) and electrical conductivity (EC) must be taken into consideration to evaluate the potential for soil dispersion to occur (Hayes et al. 1990). The greater concentrations of Cl^- and SO_4^{2-} within the effluent, compared to background soil concentrations, can allow these anions to act as tracers to monitor water movement through the soil profile (Fuller 2001). Understanding the potential irrigation rates based on effluent and soil chemistry, along with crop selection, are key to evaluating the use of KPME and WAS as sources of irrigation water.

1.6 RESEARCH BENEFITS

Effluents will require different management strategies depending upon their chemical content. For Kraft pulp mills, managing the Na^+ and salinity levels of effluents will need two approaches: one short-term, the second long-term. Short term, the use of Ca-based soil amendments (like $CaCl_2$ or $CaSO_4$) or elemental S may be options, or, possibly even acidification of the effluent stream to deal with high concentrations of HCO_3^-. However, over the long term they could also be costly. Long-term life cycle analyses or a system-based approach to sodium reduction in the effluent stream should be conducted. There may be opportunities to divert other waste streams out of the effluent system, which contribute significantly to the concentrations of Na^+, Cl^-, and SO_4^{2-}; this may include potential chemical or filtration technologies.

1.7 THESIS OUTLINE

To determine the suitability of Kraft pulp mill effluent for irrigation programs three growth chamber studies and one field study were conducted over a five-year period. The way in which these are presented in this thesis are outlined in Figure 1.1. The objectives of the research were:

1. Growth Chamber Study #1 (Chapters 2 and 3): To compare, under growth chamber conditions, Kraft pulp mill secondary (WAS) and final (KPME) effluent to a municipal effluent with respect to soil chemistry, plant nutrient uptake, and growth of hybrid poplar and reed canarygrass,

2. Growth Chamber Study #2 (Chapter 4): To evaluate the potential, under growth chamber conditions, of diluting KPME with distilled water to simulate the effects precipitation may have on soil chemistry, plant nutrient uptake, and growth of hybrid poplar,

3. Growth Chamber Study # (Chapter 5): To evaluate the effect, under growth chamber conditions, of the conjunctive use of diluted combinations of final (KPME) and secondary (WAS) Kraft pulp mill effluents, along with calcium amendments, on soil chemistry, plant nutrient uptake, and growth of winter wheat, and

4. Field Study (Chapter 6): To evaluate the soil chemistry and soil moisture trends, under field conditions, of areas planted with hybrid poplar or hybrid poplar intercropped with alsike clover and timothy, after five years of no irrigation, or three years of irrigation with KPME or water followed by two years with no irrigation.

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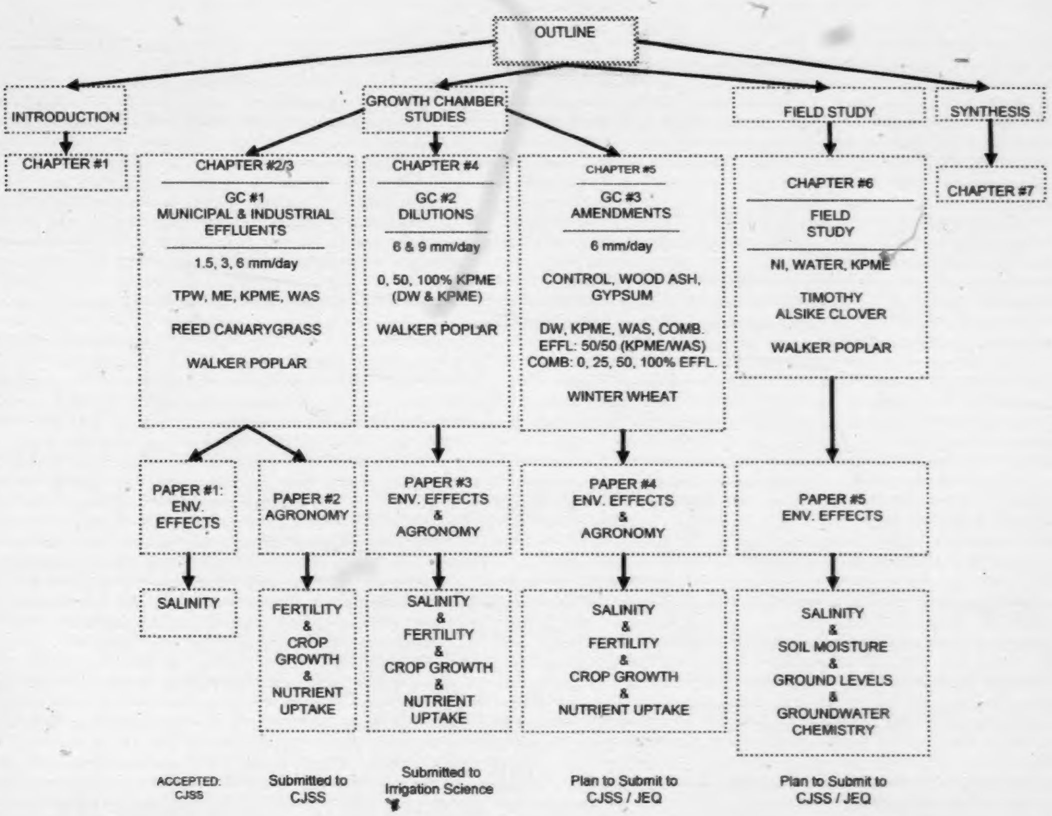
OUTLINE
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SALINITY
FERTILITY & CROP GROWTH & NUTRIENT UPTAKE
SALINITY & FERTILITY & CROP GROWTH & NUTRIENT UPTAKE
SALINITY & FERTILITY & CROP GROWTH & NUTRIENT UPTAKE
SALINITY & SOIL MOISTURE & GROUND LEVELS & GROUNDWATER CHEMISTRY
ACCEPTED: CJSS
Submitted to CJSS
Submitted to Irrigation Science
Plan to Submit to CJSS / JEQ
Plan to Submit to CJSS / JEQ

Figure 1.1. Chapter outline showing study of rates (i.e., 1.5, 3, 6 and 9 mm d^{-1}), crops (i.e., alsike clover, reed canarygrass, timothy, winter wheat and hybrid poplar) and effluents (i.e., DW – distilled water; TPW – tap water; ME - municipal effluent; KPME – Kraft pulp mill effluent; WAS - waste activated sludge) used in the three growth chamber (GC) and field studies. NI = Non-Irrigated. Bottom row shows journals which manuscripts have been or will be submitted to (CJSS – Can. J. Soil Sci – Canadian Journal of Soil Science; JEQ – Journal of Environmental Quality)

2. EFFECT OF MUNICIPAL AND PULP MILL EFFLUENTS ON THE CHEMICAL PROPERTIES AND NUTRIENT STATUS OF A COARSE TEXTURED BRUNISOL IN A GROWTH CHAMBER STUDY

In recent years there has been a growing concern over the availability and quality of ground and surface potable water sources. As the population continues to expand in rural, agricultural, and industrial areas, so does the requirement for potable water and the production of effluents. These effluents often contain high levels of nutrients, dissolved salts, and trace elements, raising environmental concerns (Sparling et al. 2001). As a result, industries, municipalities and the agricultural sector (Roygard et al. 2001; Sparling et al. 2001) are looking towards alternative ways of managing them in an environmentally acceptable way. The common method of effluent management for municipalities and industry has been to discharge effluent after treatment into nearby rivers or lakes, although land application treatments are becoming a favourable option through injection or irrigation systems (Sparling et al. 2001).

To reduce potential adverse impacts of waste disposal on the environment, strict regulations and guidelines have been developed (Myers et al. 1999; Alberta Environment 2000), further enhancing the need for alternative uses of effluents to preserve potable sources of water (Bond 1998; Halliwell et al. 2001; Roygard et al. 2001). Several projects with poplar, eucalyptus, (Myers et al. 1996; Roygard et al. 2001) and pine (Myers et al. 1996) found Effluent irrigation to be a viable management option while providing economic benefits through increased crop yields and shorter rotations in tree plantations (Menz and Grist 1997; Carlson and Berger 1998). Effluent irrigation provides a re-use opportunity for industries and municipalities, with effluents providing nutrients and water for plant growth. Some municipalities in Canada, the United States and Australia utilize spray irrigation systems on agricultural land for effluent disposal, although concerns exist with the use of effluent on potential food crops (Hansen et al. 1980; Neilsen et al. 1989; Carlson 1992; Mancino and Pepper 1992).

Pulp mill effluents contain nutrients such as nitrogen (N) and phosphorus (P) required for plant growth but they also contain dissolved salt ions [e.g., potassium (K^+), sodium (Na^+), sulfate (SO_4^{2-}), and chlorine (Cl^-)] and trace elements [e.g., boron (B), zinc (Zn)] that could pose environmental problems. Effluent irrigation raises concerns about long term site sustainability, soil salinization, increased sodicity and surface and groundwater contamination (Balks et al. 1998; Bond 1998). Table 9.1 and Table 9.2 (Appendix – B) show some of the guidelines and parameters which should be considered when considering effluents as an irrigation source. Irrigation with sodic (high Na^+) or saline (high EC) effluents could potentially have negative impacts on soil physical and chemical properties (e.g., salt accumulation within the root zone). Pulp mill effluents decreased alfalfa yields while increasing soil solution pH and sodium adsorption ratio (SAR) (Hayman and Smith 1979). Irrigation of poplar with effluent provided good growth but increased levels of SO_4^{2-}, Na^+, and Cl^- in groundwater (Hansen et al. 1980). Reed canarygrass irrigated with saline effluent reduced soil solution SAR provided Na^+ was balanced by calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the effluent (Bole et al. 1981) or through applications of gypsum (Howe and Wagner 1996). To ameliorate these problems, excess irrigation water or precipitation can be used to flush salts from the root zone (Beltran 1999) or applications of gypsum or lime products could ameliorate salt levels (Howe and Wagner 1996).

If effluents are being used as an irrigation source (IS), their SAR and electrical conductivity (ECw) must be taken into consideration. Salinity reduces the potential of Na^+ to disperse soil particles and maintain the existing soil structure provided threshold concentrations are not exceeded (Hayes et al. 1990). High concentrations of salts in the soil often result in drought-like conditions for plants due to reduced osmotic potentials (Shani and Dudley 2001). Effluents containing dissolved organic matter (Levy et al. 1999) or high Na^+ (Balks et al. 1998; Halliwell et al. 2001; Sparling et al. 2001) can lead to soil dispersion with concomitant reductions in hydraulic conductivity and infiltration rate (Magesan et al. 1999), thereby indirectly influencing potential productivity of agricultural and silvicultural crops.

Crop selection will play an important role in an effluent irrigation program and can be tailored to suit the intended function of the program (i.e., water versus nutrient removal). Tolerances of selected crops to exchangeable sodium and salinity are shown in Table 8.1 and Table 8.2 (Appendix – A). Tesar and Knezek (1982) found alfalfa (*Medicago sativa* L.) produced higher yields at lower application rates (i.e., 2.5 and 5 cm wk^{-1}) of municipal effluent due to lower amounts of applied nitrogen, while at higher rates (i.e., 7.5 cm wk^{-1}) crops like corn (*Zea mays* L.), sorgum (*Sorghum bicolor* L.), reed canarygrass (*Phalaris arundinacea* L.) and tall fescue (*Festuca arundinacea* Schreb.) yielded higher biomass. They found that reed canarygrass and tall fescue persisted longer over the five-year study period than smooth brome (*Bromus inermis* L.) or timothy (*Phleum pratense* L.) with reed canarygrass removing more applied N than any other perennial or annual grasses at all three application rates. Tesar and Knezek (1982) recommended that forage end use should be considered in addition to the role played in an effluent management program. For example, if forage use and value are important, orchard grass (*Dactylis glomerata* L.) may be more suitable whereas if forage value is not an issue, reed canarygrass may be the first choice. Forage species can also be important when considering effluent quality and application rates during irrigation seasons. Alfalfa may utilize more water if the effluent has low N, while reed canarygrass or corn could potentially utilize more effluent with a higher N.

Only a few studies have been conducted using pulp or paper mill effluents as sources of irrigation water. Examples include: a field study involving flood irrigation (USA, Hansen et al. 1980); use of gypsum amendments with papermill effluent in a greenhouse study (USA, Howe and Wagner 1996); field study on a site irrigated for 15 years with pulpmill effluent (USA, Howe and Wagner 1999); a study of papermill impacts on groundwater quality focusing on heavy metals and organochlorine residues (India, Rekha et al. 2004); an irrigation modeling study using Kraft mill effluent (Chile, Navia et al. 2006); and a lysimeter study using thermo-mechanical pulp mill effluent as an irrigation water source (New Zealand, Wang et al. 2005).

An understanding of effluent effects on soil, water, and vegetation should improve the chances of sustainable reuse. Sustainable reuse will maximize productive use and minimizes environmental impacts, a better understanding of their effects on soil and vegetation is required, particularly the impact of soil salt loading. This understanding will in turn lead to environmentally sustainable application rates. The objective of this growth chamber study was to determine the effects of a final effluent and waste activated sludge from a Kraft pulp mill, and a final municipal effluent that has undergone secondary treatment on selected soil chemical properties, specifically soluble salts as a function of application rate. The effects of such applications on nutrient content for availability and plant uptake are being addressed in a subsequent paper.

2.1 MATERIALS AND METHODS

2.1.1 Experimental Design and Treatments

Soil samples were collected from a field south of the Alberta-Pacific Forest Industries pulp mill near Boyle, Alberta, Canada. The site is 200 km northeast of Edmonton at 54° 55' latitude and 112° 52' longitude in the Athabasca region of the boreal forest. The top 20 cm of the Ap horizon of a coarse textured Eluviated Dystric Brunisol from a cultivated field was collected for use in this growth chamber study. The physical and chemical properties of the soil are given in Table 1. The area where the soils were collected consist of Brunisols, Orthic Gray Luvisols, and Humic Eluviated Gleysols (70% Tawatinaw series, O.GL; 20% Codesa Complex series, B and O.GL; and 10% Mapova series, H.EGL) based on the soil survey of the Tawatinaw map sheet (83-I) (Kjearsgaard 1972). The soils at the study site were classified as Eluviated Dystric Brunisols in the Agriculture Feasibility Study (Table 13.1 to Table 13.5, Appendix – F; Proudfoot 2000). The site slopes west and northwest with 1 to 5% slope and undulating topography. The Athabasca region receives 503 mm of precipitation annually (Environment Canada 2002), of which 67% occurs during the growing season from May to September. The remainder of the precipitation is in the form of either rain or snow but occurs from October to April outside of the growing season.

Two plant species, reed canarygrass (*Phalaris arundinacea* L. cv. Vantage) and hybrid poplar (*Populus deltoides* x *P. petrowskyana* L. var. Walker) were used, based on their success in other effluent studies and their high water and nutrient use capabilities. For each plant species, a completely randomized design with four water sources and three application rates, replicated four times, was used.

Effluents used in this study were a final effluent (KPME) and a waste activated sludge (WAS) from a Kraft pulp mill; a final municipal effluent (ME) which has undergone secondary treatment, and tap water (TPW) from the City of Edmonton serving as a control. Effluents were collected from the pulp mill and a local municipality on a weekly basis, transported to a growth chamber, stored at room temperature (15°C) and later analyzed by EnviroTest Laboratories (Edmonton, AB) (Table 2.2 and Table 2.3). Effluent and water samples were analyzed using methods outlined by the American Public Health Association (1998) for pH (Method 4500-H), electrical conductivity (EC, Method 2510), alkalinity (Method 2320), total dissolved solids (TDS), total organic carbon (TOC, Method 5310B) and total Kjeldahl nitrogen (TKN, Method 4500N-C). Method 3120B ICP-OES was used to quantify various ions in solution (i.e., sulphate, calcium, potassium, magnesium, and sodium). Chloride was determined colorimetrically (Method 4500; APHA 1998).

Buckets, 20-L in size [39 cm x 28.5 cm (inside diameter)], were filled with 30 cm of top soil overlying 6 cm of sand, the latter to prevent soil loss from the bottom of the bucket and to facilitate drainage. Hybrid poplar cuttings (15 cm) were planted in styroblocks and grown for two weeks after which one cutting was transferred to each bucket. Fifty milligrams of reed canarygrass seed was mixed with 1 kg of topsoil and spread evenly over the top of the bucket. This seed/soil mix was covered with 1.5 cm of soil, which was used for the upper 30 cm and watered with distilled water for two weeks. Hybrid poplar and reed canarygrass were watered with 200 mL every two days prior to effluent applications.

Application rates were selected based on an Agricultural Feasibility Report conducted for the field site located on the east side of NE1/4 17-68-19 W4th (Proudfoot 2000). The seasonal moisture requirement of a young hybrid poplar plantation was estimated to be 375 mm in this report. Over an 18-week (early May to mid September) irrigation schedule equates to just less than 3 mm d^{-1}. Daily application rates of 1.5 (half), 3 (full) and 6 (double) mm d^{-1} were selected to provide the water requirement based on this estimate. Table 2.2 contains the chemical analyses of the TPW and the effluents and Table 2.3 the calculated loadings at the 6 mm d^{-1} rate. Effluent and control treatments were applied to provide the equivalent of 1.5, 3, and 6 mm d^{-1} (96, 192, 384 mL d^{-1}). During the study, at these rates, 10.3, 20.7, and 41.3 L were applied to reed canarygrass and 8.2, 16.5, and 32.9 L to hybrid poplar, respectively. The study containing reed canarygrass lasted 121 days with effluent applications beginning at Day 13. Reed canarygrass was harvested at Day 74 (1st Cut) and Day 121 (2nd Cut). Hybrid poplar trees were transplanted on Day 14 and effluent applications began on Day 21. Hybrid poplar harvesting occurred 86 days later, 108 days after the study began. Soil samples were taken when reed canarygrass (Day 121) and hybrid poplar (Day 108) were harvested.

Growth chamber conditions were a 16:8 h (light:dark) photoperiod at an average air temperature of 15:12°C (day:night) for four weeks up to plant establishment, after which the temperature was increased to 20:15°C (day:night). During the growing period, buckets were rotated weekly to compensate for potential spatial variations in growth chamber conditions.

2.1.2 Soil Analyses

Soil samples were taken using a 7.5-cm soil auger from two depth increments of 0-10 cm and 10-20 cm from three locations between the centre and circumference of each bucket of the RCG and HYBP at the completion of the study. Ground soil samples (2 mm) were analyzed by EnviroTest Laboratories (Edmonton, AB; now ALS Laboratory Group) for total organic carbon (TOC) and total Kjeldahl nitrogen (TKN). Total organic carbon was determined using the Walkley Black method (Tiessen and Moir 1993) with the soil sample treated with potassium dichromate ($K_2Cr_2O_7$) and sulphuric acid (H_2SO_4). The oxidized organic carbon was determined by back-titrating the remaining non-reduced dichromate with ferrous ammonium sulfate ($(NH_4)_2Fe(SO_4)_2{*}6H_2O$). Total Kjeldahl nitrogen was determined using the method outlined by Nelson and Sommers (1996); the organic nitrogen in soil is converted to ammonia nitrogen using sulfuric acid with copper sulphate ($CuSO_4$) and potassium sulphate (K_2SO_4) as catalysts. The ammonia is then determined by distillation into boric acid and titration with standard acid.

Soil solution pH (Hendershot et al. 1993), electrical conductivity (EC), sodium adsorption ratio (SAR) and soluble Ca^{2+}, Cl^-, K^+, Mg^{2+}, Na^+, SO_4^{2-}, (Janzen 1993) and Cl (American Public Health Association 1998) were measured on a saturated paste extract. Deionized water was added to the soil until it was saturated, then it was left overnight to equilibrate. After equilibration, an extract was obtained by vacuum filtration and cations (Ca^{2+}, K^+, Mg^{2+}, and Na^+) and anions (SO_4^{2-}

) in the extract were determined with an Inductively Coupled Plasma Optical Emission Spectrophotometer (ICP-OES) (Janzen 1993) and pH and EC of the saturated paste extract (ECe) were measured using a pH and electrical conductivity meter, respectively. Soluble Cl^- was analyzed using the mercuric thiocyanate colorimetric method and quantified using Technicon Autoanalyzer (APHA 1998). Equation 2.1 was used to convert saturated paste extract results from mg L^{-1} to mg kg^{-1} and then analyzed statistically.

Equation 2.1. $$\text{mg kg}^{-1} = \text{mg L}^{-1} * \%\ \text{Saturation}/100$$

2.1.3 Statistical Analyses

The study design consisted of a completely randomized design with four irrigation treatments and three rates, replicated four times. A two-way analysis of variance (ANOVA) was conducted on saturated paste extract analyses using irrigation source (i.e., KPME, WAS, ME, and TPW) and application rate (i.e., 1.5, 3, 6 mm d^{-1}) as main factors. Analyses was conducted using the statistical program SAS (SAS Institute Inc. 2001). Statistical differences among means were determined using Tukey's HSD test and all statements of significance made at P=0.05. Statistical differences among means for the main effects (i.e., irrigation source (IS) and rate (R)) or respective interactions (i.e., ISxR) were only determined when F was significant.

2.2 RESULTS AND DISCUSSION

2.2.1 Irrigation Sources

For each of the irrigation sources SAR was adjusted (SAR_{adj}) according to Ayers and Westcot (1994) to account for the high HCO_3^- levels in the Kraft pulp mill effluents. Data for long-term data for KPME and the four irrigation sources used in this experiment were plotted in Piper diagrams (Figure 10.1 to Figure 10.5; Appendix – C). Plotting long-term KPME data in the Piper Diagrams show, the dominant cations being Na^+ + K^+ (~60-75%) in solution followed by Ca^{2+} (~30-35%), and Mg^{2+} at (~5%), while SO_4^{2-} (~45-65%) was the dominant anion in solution followed by HCO_3^- + CO_3^{2-} ranged from (~20-35%), and Cl^- (15-25%) (Figure 10.1). The major cations in solution of the control (TPW) was dominated by Ca^{2+} (~63%) followed by Mg^{2+} (~30%) and Na^+ + K^+ (~7%) in solution, while anions were dominated by SO_4^{2-} (~37%), HCO_3^- + CO_3^{2-} (60%), and Cl^- (~3%) in solution (Figure 10.2). For the municipal effluent (ME), dominant cations in solution were Na^+ + K^+ (~50%), followed by Ca^{2+} (~30%) and Mg^{+2} (~20%) in solution, while anions were dominated by HCO_3^- + CO_3^{2-} (~63%), Cl^- (~22%), and then SO_4^{2-} (~15%) (Figure 10.3). Data collected from this growth chamber experiment for KPME (Figure 10.4) were comparable to the long-term values. For the waste activated sludge (WAS), dominant cations in solution were Na^+ (~70%), followed by Ca^{2+} (~23%) and Mg^{+2} (~7%), while anions were dominated by HCO_3^- + CO_3^{2-} (50%), SO_4^{2-} (35%), and Cl^- (15%) (Figure 10.5).

Calcium, CO_3^{2-} and HCO_3^- in the effluent will likely form precipitates in the soil, removing Ca and thereby increasing the deleterious effects of Na^+ on soil properties (Ayers and Westcot 1994; Halliwell et al. 2001). According to FAO water quality standards (Ayers and Westcot 1994), the KPME used in this study would be considered 'potentially hazardous' for use in irrigation. Using SAR_{adj} for the long-term data (1993 to 2002) of 10.5 for the KPME it would lie between the 'potential hazardous' and 'safe' categories. According to Steppuhn and Curtin (1993), the effluents used in this study had SAR and salinity values marginally above those considered suitable for routine use in irrigation and their use would require monitoring. Effluents used in this study have been approved for use by the appropriate provincial ministry, with monitoring required.

The WAS effluent was highest of all four treatments in most parameters, especially TOC, TKN, HCO_3^-, Cl^-, Ca^{2+}, K^+, Na^+ and EC with a high SAR (Table 2.2). The KPME effluent was highest in SO_4^{2-} and close to the WAS effluent in Cl^-, Ca^{2+}, Na^+ and ECw and adjusted SAR (SAR_{adj}). The ME effluent was moderately high in TKN, HCO_3^- and ECw. The WAS effluent was both a carbon and nitrogen source, unlike the other effluents, while the ME effluent had a moderate level of TKN. Chloride, which can be used as a tracer for effluent movement through the soil, was similarly high in both KPME and WAS effluents and moderately high in the ME effluent. Thus elevated soil levels for TOC, TKN, and HCO_3^- could be expected under WAS effluent irrigation and SO_4^{2-}, Cl^-, Ca^{2+}, K^+, Na^+, EC, and SAR under KPME and WAS effluent irrigation. Most parameters for the ME effluent were slightly higher than those for the TPW, but rarely near the levels of either KPME or WAS effluents. Effects on pH due to effluent irrigation were not expected.

Municipal effluent (ME) and KPME are both final treated effluents that have undergone primary and secondary treatment and can be discharged to receiving waters, such as lakes or rivers. Waste activated sludge (WAS) may have been circulated through a treatment system but still contains a greater concentration of organic carbon or nitrogen than either ME or KPME effluents. Effluents such as WAS, or liquid manures (Howe and Wagner 1996), could thus increase nutrients within an effluent irrigation stream while final effluents would provide a water source. Blending effluent streams like these would help dilute nutrients in secondary effluents so loadings of nutrients like nitrogen and phosphorus could be better managed and perhaps be more sustainable for long-term use.

2.2.2 pH, Total Organic Carbon and Total Kjeldahl Nitrogen

In soils planted with reed canarygrass (Table 2.4) pH of the 0-10 cm depth increment was significantly greater in the WAS treatment compared to that of the KPME, ME, and control treatments with the exception of the 3 and 6 mm d^{-1} KPME treatment. In the lower depth increment, soil pH did not show any trends with effluent treatment or rates under reed canarygrass (Table 2.4). In soils planted with hybrid poplar (Table 2.5) pHs tended to be greater in the 3 and 6 mm d^{-1} WAS treatment but were not significantly different from the KPME or 6 mm d^{-1} control treatments. Under hybrid poplar soil pH in the 10-20 cm depth increment showed a significant rate effect with pH for the 6 mm d^{-1} rate similar to that for the 3 mm d^{-1} rate but significantly greater than that for the 1.5 mm d^{-1} treatment (Table 2.5). The addition of CO_3^{2-} or HCO_3^- in the Kraft pulp mill effluents may have contributed to the increase in soil pH of the irrigated soils (Harivandi 1999). The addition of CO_3^{2-} (Equation 2.2) or HCO_3^- (Equation 2.3) to soils results in the precipitation with Ca^{2+} or Mg^{2+} to form $CaCO_3$ or $MgCO_3$. The $CaCO_3$ (or $MgCO_3$) then hydrolyzes (Equation 2.4) to a strong base, calcium hydroxide ($Ca(OH)_2$), and a weak acid, carbonic acid (H_2CO_3), causing pH to increase.

Equation 2.2: $CO_3^{-2}{}_{(aq)} + Ca^{2+} \rightarrow CaCO_{3(s)}$

Equation 2.3: $2HCO_3^{-}{}_{(aq)} + Ca^{2+} \rightarrow Ca(HCO_3)_{2(aq)} \rightarrow CaCO_{3(s)} + H_2O_{(l)} + CO_{2(g)}$

Equation 2.4: $CaCO_{3(s)} + H_2O_{(l)} \rightarrow Ca(OH)_{2(aq)} + H_2CO_{3(aq)}$

Total organic carbon (Table 2.4; TOC) in the 0-10 cm depth increment showed a significant irrigation source effect. Under reed canarygrass, soils irrigated with WAS tended to have significantly greater TOC concentrations, attributed to higher TOC of the WAS effluent. This was likely due to the lower solids contents, since a majority of the solids have settled out of the ME and KPME, relative to the WAS, in which this has not occurred. However, this did not explain the high TOC in soils irrigated with the 6 mm d^{-1} TPW. No significant differences were observed for TOC among TPW, ME, or KPME. In the 10-20 cm depth increment no significant differences were observed amongst treatments seeded with reed canarygrass. In soils planted with hybrid poplar (Table 2.5) a significant irrigation source effect for TOC was observed in the 0-10 cm. In the 0-10 cm depth increment, TOC in WAS treatments was significantly greater than that measured in TPW and ME, but not that in KPME; attributed to the increased TOC in the WAS compared to TPW and ME. In the 10-20 cm depth increment, the only significant differences measured were between the 1.5 and 6 mm d^{-1} TPW treatments and the 6 mm d^{-1} WAS treatment; WAS being significantly greater than both TPW treatments.

The WAS treatment significantly increased TKN in the 0-10 cm depth increment for the 3 and 6 mm d^{-1} application rates under reed canarygrass (Table 2.4) and hybrid poplar (Table 2.5). In the 10-20 cm depth increment the WAS treatment significantly increased TKN under reed canarygrass but not under hybrid poplar. In the 10-20 cm depth increment under reed canarygrass, TKN was significantly greater in the WAS treatments than the control, but neither the control nor the WAS treatment was significantly different from the other two treatments. While a significant ISxR effect was measured in the 10-20 cm depth increment, the significantly greater TKN in the 1.5 mm d^{-1} treatment could be attributed to plant uptake, but does not explain the non-significant differences amongst the remaining treatments.

2.2.3 ECe, SAR and Soluble Salt Content

Pulp mill effluents significantly increased the ECe of both depth increments compared to TPW under reed canarygrass (Table 2.6 and Table 2.7) and hybrid poplar (Table 2.7 and Table 2.8), more so with hybrid poplar. This was unexpected as more effluent was applied to reed canarygrass; as a result, the total salt loadings would have been higher. In the 10-20 cm depth increment, there was no significant difference between control and ME treatments in soils planted with either reed canarygrass or hybrid poplar. For both pulp mill effluents, the ECe from this depth increment increased and were close to those from the 0-10 cm depth increment. Thus, an application rate between 3 to 6 mm d^{-1} would likely provide enough water for plant uptake and some leaching.

In the 0-10 cm depth increment under reed canarygrass (Table 2.6) or hybrid poplar (Table

2.8), application of Kraft pulp mill effluents significantly increased soil SAR and soluble Na^+ relative to the control. SAR increased with increasing application rate except under hybrid poplar irrigated with KPME; for the 3 mm d^{-1} treatment it was greater than that of the 6 mm d^{-1}. Soluble Na^+ in the soil extracts followed the same trend as SAR in the soil as expected. No significant differences were observed between control or ME treatments in the saturated paste extracts for either soluble Na^+ or SAR for soils planted with either reed canarygrass or hybrid poplar. Pulp mill effluents significantly increased soluble Na^+ in both depth increments with increasing application rate. Howe and Wagner (1999) found soil EC and Na^+ concentrations in irrigated soil profiles to be significantly greater than within those of non-irrigated soils 12 years after irrigation had ceased. Rates used in their study were 100 mm per month for 8 months over the course of 15 years.

Soluble K^+ of soils under reed canarygrass (Table 2.6) in the 0-10 cm depth increment decreased with increasing application rate for TPW, ME, and KPME but not WAS treatments. In the 10-20 cm depth increment (Table 2.7), this trend only occurred for the TPW and ME treatments. For both pulp mill treatments, soluble K^+ decreased with increasing application rate between 1.5 and 3 mm d^{-1} but increased between the 3 and 6 mm d^{-1} application rates. Soils under hybrid poplar (Table 2.8) in the 0-10 cm depth increment showed the opposite trend; an increase then a decrease for the TPW, ME, and KPME treatments. Soluble K^+ in soils irrigated with WAS, in the 0-10 cm depth increment, and in soils irrigated with ME, KPME, and WAS treatments from the 10-20 cm (Table 2.9) depth increment increased with increasing application rate. Only the TPW treatments in this depth increment showed a decrease in soluble K^+ with increasing application rate.

Soluble Ca^{2+} and Mg^{2+} were increased because of irrigations with KPME and WAS under reed canarygrass (Table 2.6). In the 0-10 cm depth increment, soluble Ca^{2+} and Mg^{2+} were significantly increased by each of the three KPME and WAS application rates compared to the equivalent application rate of TPW. Calcium and Mg^{2+} in the lower depth increment of the KPME and WAS treatments increased with increasing application rate, except for Ca^{2+} within the WAS treatments where an increase was observed between 1.5 and 3 mm d^{-1} but a decrease between 3 and 6 mm d^{-1}. This could indicate possible leaching from the uppermost depth increment in these treatments. In the 0-10 cm depth increment in soils under hybrid poplar (Table 2.8), soluble Ca^{2+} and Mg^{2+} in the soils irrigated with WAS decreased with increasing application rate. The soluble Ca^{2+} and Mg^{2+} in soils irrigated with TPW, ME, and KPME increased then decreased with increasing application rate. In the lower depth increment, Ca^{2+} and Mg^{2+} in soils irrigated with TPW decreased with increasing application rate. Soluble Ca^{2+} in soils irrigated with KPME and WAS, and soluble Mg^{2+} in soils irrigate with WAS increased between 1.5 and 3 mm d^{-1}, but decreased between 3 and 6 mm d^{-1}. Only soluble Mg^{2+} in soils irrigated with ME and KPME increased with increasing application rate.

In soils planted with reed canarygrass soluble Cl^-, in the 0-10 cm (Table 2.6) depth, decreased with increasing application rates of TPW and WAS but not those irrigated with ME or KPME. In the ME treatment, Cl^- decreased, then increased, with increasing application rate, while in the KPME treatment Cl^- increased, then decreased, with increasing application rate. In the 10-20 cm depth increment of the TPW treatment (Table 2.7), Cl^- decreased with increasing application rate while for all three effluent treatments, Cl^- increased with increasing application rates. Soluble Cl^- was significantly greater at all three rates in KPME and WAS treatments compared to TPW, but not compared to ME. At all three rates both pulp mill effluents significantly increased soluble Cl^-, compared to their corresponding TPW treatment, in both depth increments. In soils planted with hybrid poplar (Table 2.8), soluble Cl^-, in 0-10 cm depth increment was greatest within the 3 mm d^{-1} treatment, a trend evident for all three effluent treatments and the control. In the 10-20 cm depth increment (Table 2.9), Cl^- increased with increasing application rate for all three effluent treatments, similar to the trend observed in soils with reed canarygrass. In the 0-10 cm depth increment, soluble Cl^- because of all three effluents were significant greater compared to their corresponding TPW treatment; except for the 6 mm d^{-1} KPME application rate. Increases in Cl^- within the soil will decrease yield of hybrid poplar (Shannon et al. 1999) unless managed within the rootzone, but could also pose groundwater quality issues (Hansen et al. 1980). The increased loadings of either SO_4^{2-} or Cl^- levels in the groundwater could pose aesthetic problems if groundwater is also used as a potable or drinking water source. Chloride levels within the effluent provide a unique opportunity to utilize Cl^- as a tracer (Fuller 2001) within the soil profile to monitor potential environmental risks to groundwater. Soluble SO_4^{2-} in the effluent treatments increased with increasing application rate, significantly greater in soils irrigated with the KPME and WAS than in soils irrigated with control or ME for both reed canarygrass (Table 2.6 and Table 2.7) and hybrid poplar (Table 2.8 and Table 2.9) in both depth increments.

With higher soluble Na^+ in effluent irrigated soils, significantly higher SAR and ECe, in saturated paste extracts, were found in this study; results were in agreement with those of several other researchers (Hayman and Smith 1979; Hayes et al., 1990; Balks et al. 1998). Rengasamy and Olsson (1993) suggested that, over time, leaching can decrease EC while SAR remains elevated and suggested soil sodification will occur unless sufficient Ca^{2+} and/or Mg^{2+} are present in the soil profile. Hayes et al. (1990) found EC was significantly higher under effluent irrigation compared to potable water; the increase was small but soil Na^+ increased significantly. With either plant species, Na^+ increased with increasing application rates for KPME and WAS treatments. Ca^{2+} and Mg^{2+} did not differ significantly amongst the three rates for the KPME treatment, while Mg^{2+} increased with increasing application rate for the WAS treatment. This may be due to Ca^{2+} and Mg^{2+} at the soil surface and in the effluent forming insoluble precipitates because of the addition of CO_3^{2-} and HCO_3^- from Kraft pulp mill effluents, further increasing SAR in 0-10 cm and 10-20 cm depth increments. Removal of Ca^{2+} and Mg^{2+} through precipitation will further increase the deleterious effects of Na^+ on soil properties (Ayers and Westcot 1994; Halliwell et al. 2001). Use of organic amendments or Ca^{2+} sources such as gypsum, or wood ash for low pH soils, could alleviate these issues (Howe and Wagner 1996).

2.2.4 Management Implications

In this study, soluble salts were elevated most often in WAS and KPME treatments and in some cases the ME, consistent with the chemical composition of these effluents. Salinity was elevated in all three effluent irrigation treatments at the 3 and 6 mm d^{-1} rates. However, soluble salts within pulp mill effluents resulted in much greater increases in ECe and SAR, in saturated paste extracts, relative to the ME and control treatments. Municipal effluent did not significantly increase soil solution EC or SAR compared to initial conditions, unlike the two pulp mill effluents. Sodium, SO_4^{2-}, and Cl^- were high in soils treated with Kraft pulp mill effluents since dissolved salts are part of the Kraft pulp process and are at significantly higher concentrations than in municipal tap water or final effluent (Smook 1989). For both Kraft pulp mill effluents, leaching most likely played a role in removal of Na^+ from the 0-10 cm depth increment at higher application rates as Na^+ in the 10-20 increment was significantly greater with applications at 6 mm d^{-1} compared to either 1.5 or 3 mm d^{-1} in soils planted with either reed canarygrass or hybrid poplar.

The long-term impacts of effluent irrigation on soil physical properties and exchangeable solute effect on leaching will depend on the amount of Na^+, Ca^{2+}, and Mg^{2+} adsorbed by the soil (Rengasamy and Olsson 1993). Adsorbed cations and anions will play an important role in the long-term supply of solutes into soil solution even after irrigation has ceased (Howe and Wagner 1999). The Cl^- or SO_4^{2-} can be used as tracers to monitor solute movement through the soil profile and to examine impacts on groundwater.

Increasing the amount of soluble Ca^{2+} and Mg^{2+} in soil solution will displace Na^+ on exchange sites, allowing Na to be leached below the rootzone. The continued use of gypsum to supply soluble Ca^{2+} may be required (Bauder and Brock 2001). Additions of elemental S to either the soil or acidification of the effluent itself will help reduce the concentrations of HCO_3^- and CO_3^{2-} present in the effluent; by not forming precipitates this will increase the amount of Ca^{2+} and Mg^{2+} in the soil solution.

Crop selection will play an important role in the success of these projects. Crops like reed canarygrass could be harvested throughout the season to remove nutrients and thus minimize accumulation within the soil profile. The total amount of effluent applied at the three treatment rates was greater with reed canarygrass than hybrid poplar. Total soil loading of K^+, Ca^{2+}, and Mg^{2+} was lower under reed canarygrass than hybrid poplar; however, accumulation of Na in the soil was similar between the two plant species, indicating more K^+, Ca^{2+}, Mg^{2+}, and Na^+ were likely removed by reed canarygrass.

Basing rates on effluent chemical characteristics is essential for any irrigation project as increasing rates increased soil loadings of soluble salts and trace elements. In this study, increasing application rates resulted in large increases in soluble salts such as Na^+, SO_4^{2-}, and Cl^-, with smaller increases in soluble Ca^{2+} and Mg^{2+}. The primary issue resulting from irrigating with KPME or WAS is most likely that increased soil concentrations of soluble ions, especially Na^+, that will lead to detrimental effects on soil properties, such as dispersion, leading to increased soil crusting and reduced infiltration (Buckland et al. 2002). Increasing effluent application rates could also increase the risk of groundwater contamination under field conditions.

2.3 CONCLUSIONS

Under continuous irrigation with saline or sodic effluents, accumulation of salts within the rooting zone could begin to limit productivity of crops with moderate to low salt tolerance. Ions, especially Na^+, contained in these effluents will likely eventually limit their use under field conditions, unless they are carefully managed. Salt loadings should be used to establish application rates for pulp mill treated and waste activated sludges, while nutrient loadings may be more suitable for municipal effluents. More information is needed on long-term effects resulting from the interaction of climatic and environmental effects along with crop management on soils irrigated with saline (high EC) or sodic (high Na^+) industrial effluents. In areas where growing seasons are short, alternative cropping systems (Bauder and Brock 2001), like agroforestry, could allow effluents to be applied for longer periods and make more efficient use of nutrients applied. Increasing amounts of effluents applied through higher application rates must consider the potential negative impacts, like salinity (Letey 1993), without proper management (Toze 2006). Either Na^+ in effluents needs to be reduced or Ca^{2+} and Mg^{2+} in effluent or receiving soils need to be increased for sustainable irrigation management with effluents. There may be an opportunity in future studies for combining gypsum, phosphogypsum, or other residual lime by-products, often produced by pulp mills, to supplement Ca^{2+} and Mg^{2+} of effluents to offset the effects of dispersion caused by Na^+ within the soil.

Kraft pulp mill and municipal effluents resulted in elevated ECe, SAR and soluble Na^+, Cl^-, and SO_4^{2-}. Crop selection influenced accumulation of K^+, Ca^{2+}, Mg^{2+}, and Na^+ in soil. Increasing application rate helped leach some salts from the upper depth increment but led to accumulation of Na^+, Cl^-, and SO_4^{2-} in the lower depth increment. All three rates of the two Kraft pulp mill effluents increased soil extract EC (>2 dS m^{-1}) and SAR (>6) above values considered acceptable for agricultural production. Leaching occurred at the two higher application rates. Therefore, addition of supplemental water by either precipitation or irrigation could help leach salts through the root zone without further increasing SAR. Further research should be conducted on the impact regional precipitation in combination with effluent treatments may have on soil properties as well as what amendments could be used to help offset accumulation of Na^+ and increased SAR in the soil. Irrigation with Kraft pulp mill effluent may be feasible on an interim basis; however, it will not be sustainable over the long term unless high concentrations of Na^+ and HCO_3^- can be addressed.

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Table 2.1. Average (n=3) values (± S.E.) of selected physical and chemical characteristics of the study soil

Characteristic	Average
Bulk Density (Mg m^{-3})	1.12
[Z] PAW (cm^{3} cm^{-3})	0.28
Texture	Loam
Sand (g kg^{-1})	35.3 ± 0.7
Silt (g kg^{-1})	44.3 ± 0.9
Clay (g kg^{-1})	20.3 ± 0.3
pH	5.9 ± 0.1
[Y] ECw (dS m^{-1})	1.8 ± 0.2
[X] CEC (cmol kg^{-1})	20.1 ± 0.2
Saturation (%)	45.7 ± 0.7
[W] SAR	0.3 ± 0.0
Ca (mg kg^{-1})	119.8 ± 15.3
K (mg kg^{-1})	2.2 ± 0.2
Mg (mg kg^{-1})	24.1 ± 2.8
Na (mg kg^{-1})	9.6 ± 0.4
Cl (mg kg^{-1})	13.2 ± 1.7
SO$_4$ (mg kg^{-1})	26.2 ± 0.9

[Z] PAW – Plant Available Water: Pressure levels chosen for the loam textured Eluviated Dystric Brunisol soil for field capacity and wilting point were 10 kPa and 1500 kPa, respectively

[X] ECw - Electrical Conductivity of irrigation source

[X] Cation exchange capacity

[W] Sodium Adsorption Ratio

Table 2.2. Selected mean (n=4) chemical and nutrient properties of control (TPW), municipal effluent (ME), Kraft pulp mill effluent (KPME) and waste activated sludge (WAS) irrigation sources

		Effluent Concentrations			
[Z] Treatment		TPW	ME	KPME	WAS
pH	pH	7.8	7.5	7.7	7.2
[Y] ECw	dS m^{-1}	0.37	1.06	2.52	2.87
[X] TDS	mg L^{-1}	0.2	0.5	1.7	1.8
		---------------- mg L^{-1} ----------------			
[W] TKN	mg L^{-1}	0.4	42.7	1.8	299.0
[V] Diss-P	mg L^{-1}	0.02	3.5	1.7	4.7
B	mg L^{-1}	0.02	0.27	0.05	0.9
Cu	mg L^{-1}	0.05	0.03	0.01	0.3
Fe	mg L^{-1}	0.07	0.36	0.17	34.5
Mn	mg L^{-1}	0.01	0.27	0.18	66.5
Zn	mg L^{-1}	0.03	0.09	0.06	12.5
HCO$_3$	mg L^{-1}	139.5	412.5	483.8	925.5
SO$_4$	mg L^{-1}	66.9	73.6	724.3	529.8
Cl	mg L^{-1}	4.5	91.0	164.3	166.0
Ca	mg L^{-1}	45.3	45.3	56.3	113.7
K	mg L^{-1}	1.0	15.7	45.1	62.6
Mg	mg L^{-1}	13.2	21.0	18.2	24.3
Na	mg L^{-1}	9.5	90.8	435.0	439.3
[U] SAR	mg L^{-1}	0.5	3.7	14.1	12.6
[T] SAR$_{adj}$	mg L^{-1}	0.3	3.3	14.5	14.5

[Z] TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge

[Y] EC - Electrical conductivity of irrigation source

[X] TDS – Total Dissolved Solids

[W] TKN – Total Kjeldahl Nitrogen

[V] Diss-P - Dissolved Phosphorus

[U] SAR - Sodium Adsorption Ratio

[T] SAR$_{adj}$ – Adjusted SAR (Ayers and Westcot 1994)

Table 2.3. Total soil loadings (mg) due to control (TPW), municipal effluent (ME), Kraft pulp mill effluent (KPME) and waste activated sludge (WAS) irrigation sources used in the study irrigation source applications at 6 mm d^{-1} for soils planted with RCG or HYBP

		Amount Applied (mg pot^{-1})							
		- Reed Canarygrass (41.3 L Applied) -				--- Hybrid Poplar (32.9 L Applied) ---			
[Z] Treatment		TPW	ME	KPME	WAS	TPW	ME	KPME	WAS
		---------- mg ----------				---------- mg ----------			
[W] TKN	mg L^{-1}	17.0	1 764	74.3	12 349	13.0	1 405	59.2	9 837
[V] Diss-P	mg L^{-1}	0.8	143	70	194	0.7	114	56	155
B	mg L^{-1}	0.8	11.2	2.1	35.1	0.7	8.9	1.6	28.0
Cu	mg L^{-1}	2.1	1.2	0.4	10	1.6	1.0	0.3	8.2
Fe	mg L^{-1}	2.9	15	7.0	1 425	2.3	11.8	5.6	1 135
Mn	mg L^{-1}	0.4	11	7.4	2 748	0.3	8.9	5.9	2 189
Zn	mg L^{-1}	1.2	3.7	2.5	517	1.0	3.0	2.0	412
HCO_3	mg L^{-1}	5 761	17 036	19 981	38 223	4 590	13 571	15 917	30 449
SO_4	mg L^{-1}	2 763	3 040	29 914	21 881	2 201	2 421	23 829	17 430
Cl	mg L^{-1}	186	3 758	6 786	6 856	148	2 994	5 405	5 461
Ca	mg L^{-1}	142.8	1 871	2 325	4 696	5 898	1 490	1 852	3 741
K	mg L^{-1}	41	648	1 863	2 585	33	517	1 484	2 060
Mg	mg L^{-1}	545	867	752	1 004	434	691	599	799
Na	mg L^{-1}	392	3 750	17 966	18 143	313	2 987	14 312	14 453
[U] SAR	mg L^{-1}								
[T] SAR_{adj}	mg L^{-1}								

[Z] TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge

[Y] EC - Electrical conductivity of irrigation source

[X] TDS – Total Dissolved Solids

[W] TKN – Total Kjeldahl Nitrogen

[V] Diss-P - Dissolved Phosphorus

[U] SAR - Sodium Adsorption Ratio

[T] SAR_{adj} – Adjusted SAR (Ayers and Westcot 1994)

Table 2.4 Average soil pH, % saturation (% Sat), TOC, and TKN at soil depth increments of 0-10 and 10-20 cm under reed canarygrass after 107 days of irrigation treatments

	--------- 0 to 10 cm ---------				--------- 10 to 20 cm ---------			
^{Z} Treatment	pH	Sat.	^{Y}TOC	^{X}TKN	pH	Sat.	TOC	TKN
		%	------ % ------			%	------- % ------	
TPW: 1.5 mm day^{-1}	6.03	45.1	2.33	0.34	6.08	43.8	2.40	0.27
TPW: 3 mm day^{-1}	6.33	50.8	2.40	0.32	6.10	46.1	2.38	0.26
TPW: 6 mm day^{-1}	6.40	46.8	3.13	0.32	6.00	45.1	2.35	0.29
ME: 1.5 mm day^{-1}	6.08	44.1	2.35	0.29	5.70	45.0	2.38	0.24
ME: 3 mm day^{-1}	6.25	44.1	2.98	0.28	5.88	49.0	2.38	0.20
ME: 6 mm day^{-1}	6.45	45.1	2.33	0.28	6.18	46.1	2.20	0.21
KPME: 1.5 mm day^{-1}	6.35	48.5	2.45	0.29	5.93	44.1	2.38	0.28
KPME: 3 mm day^{-1}	6.60	44.8	2.50	0.28	5.83	46.8	2.45	0.27
KPME: 6 mm day^{-1}	6.45	46.8	2.48	0.26	6.28	48.3	2.28	0.24
WAS: 1.5 mm day^{-1}	6.83	48.6	2.83	0.44	5.78	45.5	2.53	0.27
WAS: 3 mm day^{-1}	6.95	54.5	3.43	0.56	5.90	47.9	2.48	0.30
WAS: 6 mm day^{-1}	7.15	57.4	3.73	0.67	6.25	46.7	2.40	0.32
^{W} Application Rate								
1.5 mm day^{-1}	6.32	46.6	2.49	0.34	5.87	44.6	2.42	0.26
3 mm day^{-1}	6.53	48.6	2.83	0.36	5.93	47.4	2.42	0.26
6 mm day^{-1}	6.61	49.0	2.91	0.38	6.18	46.5	2.31	0.26
^{W} Irrigation Source								
TPW	6.25	47.6	2.62	0.33	6.06	45.0	2.38	0.27
ME	6.26	44.4	2.55	0.28	5.92	46.7	2.32	0.22
KPME	6.47	46.7	2.48	0.28	6.01	46.4	2.37	0.26
WAS	6.98	53.5	3.33	0.55	5.98	46.7	2.47	0.29
^{V}HSD$_{0.05}$								
Irrigation Source (IS)	0.12	3.6	0.48	0.08	ns	ns	ns	0.04
Application Rate (R)	0.09	ns	0.38	ns	0.12	2.3	0.12	ns
IS x R	0.27	8.1	ns	0.18	0.34	ns	ns	ns

^{Z}TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge

^{Y} TOC – Total Organic Carbon

^{X} TKN – Total Kjeldahl Nitrogen

^{W} Averages for application rate (1.5, 3, 6 mm d^{-1}) and irrigation sources (TPW, ME, KPME, WAS) main factor effects

^{V} HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

Table 2.5. Average soil pH, % saturation (% Sat), TOC, and TKN at soil depth increments of 0-10 and 10-20 cm under hybrid poplar after 86 days of irrigation treatments

	0 to 10 cm				10 to 20 cm			
[z] Treatment	pH	Sat.	TOC	TKN	pH	Sat.	TOC	TKN
		%	------- %	-------		%	------- %	-------
TPW: 1.5 mm day^{-1}	5.75	47.2	2.38	0.27	6.05	47.8	1.95	0.35
TPW: 3 mm day^{-1}	5.68	48.8	2.93	0.29	6.10	47.2	2.10	0.26
TPW: 6 mm day^{-1}	6.15	48.5	2.28	0.27	6.33	47.9	1.95	0.26
ME: 1.5 mm day^{-1}	6.03	47.2	2.08	0.36	6.03	46.3	2.15	0.28
ME: 3 mm day^{-1}	5.68	46.9	2.10	0.42	6.10	46.8	2.00	0.27
ME: 6 mm day^{-1}	5.80	50.4	2.05	0.32	6.20	47.3	2.13	0.26
KPME: 1.5 mm day^{-1}	6.03	53.4	2.03	0.34	5.98	46.8	2.27	0.27
KPME: 3 mm day^{-1}	6.10	47.9	2.88	0.30	6.10	46.4	2.25	0.26
KPME: 6 mm day^{-1}	6.55	49.2	2.18	0.31	6.33	47.2	2.18	0.27
WAS: 1.5 mm day^{-1}	6.43	50.4	2.68	0.53	6.00	48.3	2.13	0.25
WAS: 3 mm day^{-1}	6.55	53.1	4.00	0.79	6.15	49.1	2.25	0.28
WAS: 6 mm day^{-1}	7.08	54.0	3.25	1.11	6.23	48.3	2.45	0.28
[W] Application Rate								
1.5 mm day^{-1}	6.06	49.5	2.29	0.38	6.01	47.3	2.13	0.29
3 mm day^{-1}	6.00	49.1	2.98	0.45	6.11	47.4	2.15	0.27
6 mm day^{-1}	6.39	50.5	2.44	0.50	6.27	47.7	2.18	0.27
[W] Irrigation Source								
TPW	5.86	48.1	2.53	0.28	6.16	47.6	2.00	0.29
ME	5.83	48.2	2.08	0.37	6.11	46.8	2.09	0.27
KPME	6.23	50.1	2.36	0.32	6.13	46.8	2.23	0.26
WAS	6.68	52.5	3.31	0.81	6.13	48.6	2.28	0.27
[V] $HSD_{0.05}$								
Irrigation Source (IS)	0.19	5.0	0.83	0.15	ns	0.9	0.17	0.02
Application Rate (R)	0.15	3.9	0.65	ns	0.17	ns	ns	0.02
IS x R	0.43	11.1	ns	0.34	ns	ns	ns	0.05

[Z] TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge

[Y] TOC – Total Organic Carbon

[X] TKN – Total Kjeldahl Nitrogen

[W] Averages for application rate (1.5, 3, 6 mm d^{-1}) and irrigation sources (TPW, ME, KPME, WAS) main factor effects

[V] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

Table 2.6. Average electrical conductivity (ECe), sodium adsorption ratio (SAR) and soluble Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} of saturated paste extracts 0-10 depth increment for soils irrigated for 107 days with control (TPW), municipal effluent (ME), Kraft pulp mill effluents (KPME and WAS) planted with reed canarygrass

[Z]Treatment	[Y]ECe	[X]SAR	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
	$dS\ m^{-1}$		mg kg^{-1}					
TPW: 1.5 mm day^{-1}	2.3	0.8	58.5	4.9	357.8	78.4	69.3	435.3
TPW: 3 mm day^{-1}	1.7	0.9	58.0	3.5	256.5	56.5	51.3	432.8
TPW: 6 mm day^{-1}	1.1	0.9	46.8	1.7	156.5	33.8	18.5	426.0
ME: 1.5 mm day^{-1}	3.4	2.7	252.3	8.2	489.5	108.6	432.0	546.3
ME: 3 mm day^{-1}	1.8	3.0	177.5	3.9	180.3	40.6	283.8	289.3
ME: 6 mm day^{-1}	2.0	4.0	227.0	2.6	190.0	42.1	366.0	312.3
KPME: 1.5 mm day^{-1}	5.1	8.4	849.0	10.4	578.5	125.0	552.5	1872.5
KPME: 3 mm day^{-1}	6.1	13.2	1247.5	9.7	494.8	113.3	789.3	2485.0
KPME: 6 mm day^{-1}	5.2	12.4	1122.8	6.1	462.0	98.9	580.5	2542.5
WAS: 1.5 mm day^{-1}	5.3	10.4	988.0	24.9	511.3	109.3	508.5	1952.5
WAS: 3 mm day^{-1}	5.8	13.6	1262.5	20.7	499.0	99.4	427.5	2470.0
WAS: 6 mm day^{-1}	5.6	14.0	1240.0	22.0	454.3	87.0	331.8	2237.5
[W] Application Rate								
1.5 mm day^{-1}	4.0	5.5	536.9	12.1	484.3	105.3	390.6	1201.6
3 mm day^{-1}	3.8	7.7	686.4	9.4	357.6	77.4	387.9	1419.3
6 mm day^{-1}	3.5	7.8	659.1	8.1	315.7	65.4	324.2	1379.6
[W] Irrigation Source								
TPW	1.7	0.8	54.4	3.4	256.9	56.2	46.3	431.3
ME	2.4	3.2	218.9	4.9	286.6	63.8	360.6	382.6
KPME	5.5	11.3	1073.1	8.7	511.8	112.4	640.8	2300.0
WAS	5.6	12.6	1163.5	22.5	488.2	98.6	422.6	2220.0
[V] $HSD_{0.05}$								
Irrigation Source (IS)	0.6	1.0	93.7	2.1	76.6	17.4	95.4	195.5
Application Rate (R)	0.4	0.8	73.7	1.7	60.2	13.7	75.0	153.7
IS x R	1.3	2.3	210.3	4.8	171.9	39.2	214.1	438.7

[Z] TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge

[Y] ECe – Electrical Conductivity of saturate paste extracts

[X] SAR – Sodium Adsorption Ratio

[W] Averages for application rate (1.5, 3, 6 mm d^{-1}) and irrigation sources (TPW, ME, KPME, WAS) main factor effects

[V] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

Table 2.7. Average electrical conductivity (ECe), sodium adsorption ratio (SAR) and soluble Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} of saturated paste extracts for the 10-20 cm depth increment for soils irrigated for 107 days with control (TPW), municipal effluent (ME), Kraft pulp mill effluents (KPME and WAS) planted with reed canarygrass

	^{Y}ECe	^{X}SAR	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
^{Z} Treatment	dS m^{-1}		----------------	----------------	----------------	mg kg^{-1}	----------------	----------------
TPW: 1.5 mm day^{-1}	1.1	0.6	30.0	3.0	156.3	32.7	27.8	156.5
TPW: 3 mm day^{-1}	0.8	0.6	26.0	2.0	126.4	26.2	17.3	232.3
TPW: 6 mm day^{-1}	0.7	0.7	30.5	1.3	118.3	24.0	7.5	259.8
ME: 1.5 mm day^{-1}	1.9	1.0	72.5	4.2	282.0	58.7	106.8	208.3
ME: 3 mm day^{-1}	1.5	1.2	73.5	3.2	213.3	44.7	167.8	173.5
ME: 6 mm day^{-1}	1.3	2.4	119.8	1.6	142.3	28.4	189.8	232.8
KPME: 1.5 mm day^{-1}	2.8	2.7	231.0	4.8	407.0	81.6	214.0	890.8
KPME: 3 mm day^{-1}	3.2	3.6	327.3	4.2	478.3	95.8	359.8	1330.0
KPME: 6 mm day^{-1}	5.0	9.5	889.8	5.8	502.8	99.1	481.3	2120.0
WAS: 1.5 mm day^{-1}	3.0	2.4	202.0	6.8	422.3	84.2	220.5	576.5
WAS: 3 mm day^{-1}	4.2	4.2	426.0	6.2	584.8	116.3	486.0	1243.3
WAS: 6 mm day^{-1}	6.2	11.6	1150.0	7.0	548.8	124.0	763.0	2025.0
^{W} Application Rate								
1.5 mm day^{-1}	2.2	1.7	133.9	4.7	316.9	64.3	142.3	458.0
3 mm day^{-1}	2.4	2.4	213.2	3.9	350.7	70.7	257.7	744.8
6 mm day^{-1}	3.3	6.0	547.5	3.9	328.0	68.9	360.4	1159.4
^{W} Irrigation Source								
TPW	0.9	0.6	28.8	2.1	133.6	27.6	17.5	216.2
ME	1.6	1.6	88.6	3.0	212.5	43.9	154.8	204.8
KPME	3.7	5.3	482.7	4.9	462.7	92.2	351.7	1446.9
WAS	4.5	6.1	592.7	6.7	518.6	108.2	489.8	1281.6
^{V}HSD$_{0.05}$								
Irrigation Source (IS)	0.4	0.7	75.6	0.7	52.5	12.2	70.3	237.9
Application Rate (R)	0.3	0.6	59.4	0.5	ns	ns	55.3	187.0
IS x R	0.9	1.6	169.5	1.6	117.9	27.4	157.7	533.9

[Z] TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge

[Y] ECe – Electrical Conductivity of saturate paste extracts

[X] SAR – Sodium Adsorption Ratio

[W] Averages for application rate (1.5, 3, 6 mm d^{-1}) and irrigation sources (TPW, ME, KPME, WAS) main factor effects

[V] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

Table 2.8. Average electrical conductivity (ECe), sodium adsorption ratio (SAR) and soluble Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} of saturated paste extracts for the 0-10 depth increment for soils irrigated for 86 days with control (TPW), municipal effluent (ME), Kraft pulp mill effluents (KPME and WAS) planted with hybrid poplar

[Z] Treatment	[Y] ECe dS m^{-1}	[X] SAR	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
			mg kg^{-1}					
TPW: 1.5 mm day^{-1}	3.6	0.6	57.3	8.2	563.5	118.6	78.0	313.0
TPW: 3 mm day^{-1}	5.4	0.7	86.3	9.5	859.3	183.0	129.0	435.0
TPW: 6 mm day^{-1}	2.6	0.9	69.8	5.4	390.0	83.4	68.3	389.0
ME: 1.5 mm day^{-1}	4.8	2.3	253.3	13.3	663.0	143.8	366.8	338.8
ME: 3 mm day^{-1}	7.7	2.5	356.0	15.9	1108.5	238.8	573.5	393.0
ME: 6 mm day^{-1}	4.2	2.9	271.3	8.1	483.3	108.0	397.3	179.3
KPME: 1.5 mm day^{-1}	7.8	7.1	881.5	17.1	881.0	184.3	602.5	1660.0
KPME: 3 mm day^{-1}	11.8	12.3	1736.7	24.1	1043.3	273.0	1426.7	1816.7
KPME: 6 mm day^{-1}	7.1	10.6	1065.7	15.5	582.7	118.8	508.7	2266.7
WAS: 1.5 mm day^{-1}	7.9	8.9	1057.5	38.5	804.3	163.0	609.3	2030.0
WAS: 3 mm day^{-1}	8.6	11.5	1290.0	59.7	723.7	141.3	704.0	2740.0
WAS: 6 mm day^{-1}	7.6	12.7	1297.5	64.9	597.3	119.0	548.3	2212.5
[W] Application Rate								
1.5 mm day^{-1}	6.0	4.7	562.4	19.3	727.9	152.4	414.1	1085.4
3 mm day^{-1}	8.4	6.8	867.3	27.3	933.7	209.0	708.3	1346.2
6 mm day^{-1}	5.4	6.8	676.1	23.5	513.3	107.3	380.6	1261.9
[W] Irrigation Source								
TPW	3.8	0.7	71.1	7.7	604.3	128.3	91.8	379.0
ME	5.6	2.6	293.5	12.4	751.6	163.5	445.9	303.7
KPME	8.9	10.0	1228.0	18.9	835.7	192.0	846.0	1914.5
WAS	8.1	11.0	1215.0	54.4	708.4	141.1	620.5	2327.5
[V] $HSD_{0.05}$								
Irrigation Source (IS)	1.4	1.2	162.6	5.4	166.4	37.9	167.6	251.4
Application Rate (R)	1.1	1.0	127.8	4.2	130.8	29.8	131.7	197.6
IS x R	3.0	2.8	364.8	12.1	373.3	85.0	376.1	564.2

[Z] TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge

[Y] ECe – Electrical Conductivity of saturate paste extracts

[X] SAR – Sodium Adsorption Ratio

[W] Averages for application rate (1.5, 3, 6 mm d^{-1}) and irrigation sources (TPW, ME, KPME, WAS) main factor effects

[V] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

Table 2.9. Average electrical conductivity (ECe), sodium adsorption ratio (SAR) and soluble Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} of saturated paste extracts 0-10 and 10-20 cm depth increments for soils irrigated for 86 days with control (TPW), municipal effluent (ME), Kraft pulp mill effluents (KPME and WAS) planted with hybrid poplar

	^{Y}ECe	^{X}SAR	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
^{Z}Treatment	dS m^{-1}		mg kg^{-1}					
TPW: 1.5 mm day^{-1}	1.7	0.5	31.5	4.3	236.0	48.9	32.3	104.8
TPW: 3 mm day^{-1}	1.3	0.5	31.3	3.8	184.7	39.3	31.3	148.0
TPW: 6 mm day^{-1}	1.0	0.6	30.5	2.8	164.3	33.6	33.8	230.8
ME: 1.5 mm day^{-1}	1.6	0.7	43.5	4.0	301.8	42.9	69.3	92.9
ME: 3 mm day^{-1}	2.0	1.3	81.8	3.9	208.8	50.0	168.8	105.2
ME: 6 mm day^{-1}	2.2	2.1	142.0	4.2	263.8	59.2	246.3	131.2
KPME: 1.5 mm day^{-1}	3.0	2.2	191.3	6.0	403.8	79.9	137.8	527.0
KPME: 3 mm day^{-1}	4.1	4.9	451.3	7.6	498.0	97.1	283.7	1173.3
KPME: 6 mm day^{-1}	5.1	6.6	656.3	7.7	376.3	113.0	453.7	1440.0
WAS: 1.5 mm day^{-1}	2.8	1.9	162.3	7.8	405.0	80.0	120.7	500.0
WAS: 3 mm day^{-1}	5.2	4.6	492.7	9.2	653.7	123.3	348.3	1046.0
WAS: 6 mm day^{-1}	6.3	8.1	846.0	9.6	630.8	120.5	448.8	1592.5
^{W} Application Rate								
1.5 mm day^{-1}	2.3	1.3	107.2	5.5	336.6	62.9	90.0	306.2
3 mm day^{-1}	3.1	2.8	264.3	6.1	386.3	77.4	208.0	618.1
6 mm day^{-1}	3.7	4.3	418.7	6.1	358.8	81.6	295.6	848.6
^{W} Application Rate								
TPW	1.3	0.5	31.1	3.6	195.0	40.6	32.4	161.2
ME	1.9	1.3	89.1	4.0	258.1	50.7	161.4	109.8
KPME	4.1	4.5	433.0	7.1	426.0	96.7	291.7	1046.8
WAS	4.8	4.9	500.3	8.8	563.1	107.9	305.9	1046.2
$^{V}HSD_{0.05}$								
Irrigation Source (IS)	0.6	0.6	61.4	1.6	122.6	13.7	51.6	131.1
Application Rate (R)	0.5	0.4	48.2	ns	ns	10.8	40.6	103.1
IS x R	1.4	1.3	137.7	ns	275.1	30.8	115.8	294.2

[Z] TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge

[Y] ECe – Electrical Conductivity of saturate paste extracts

[X] SAR – Sodium Adsorption Ratio

[W] Averages for application rate (1.5, 3, 6 mm d^{-1}) and irrigation sources (TPW, ME, KPME, WAS) main factor effects

[V] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

3. *EFFLUENT EFFECTS ON A COARSE TEXTURED SOIL AND ASSOCIATED IMPACTS ON THE NUTRIENT CONCENTRATIONS AND GROWTH OF REED CANARYGRASS (PHALARIS ARUNDINACEA L.) AND HYBRID POPLAR (POPULUS DELTOIDES X P. PETROWSKYANA L.)*

Agricultural and industrial expansion, coupled with municipal developments, leads to competition for land and a growing need for clean, potable water. Liquid and solid wastes have been land applied in agriculture for hundreds of years, adding nutrients and water for crop growth. In recent years advances in irrigation technology and land application equipment have improved the application of these effluents. Agricultural and forest species under effluent irrigation systems can utilize the dissolved nutrients contained within the effluent (Roygard et al. 2001; Sparling et al. 2001). While providing the added economic value of multiple crops, increased total yields are a possibility in addition to reducing nutrient loading and avoiding continuous discharge to potable surface water sources. In the boreal region nutrients like nitrogen (N), phosphorus (P), and sulphur (S) tend to be deficient. These effluents can provide nutrients such as N, P, and S. However, other elements such as sodium (Na) and chloride (Cl) within the effluent can lead to environmental problems, like soil salinity and sodicity. Tolerances of selected crops to exchangeable sodium and salinity are shown in Table 8.1 and Table 8.2 (Appendix – A). There is also the potential groundwater contamination from the leaching of excessive dissolved nutrients such as N and P. Thus, regulations and guidelines for effluent irrigation have been developed in numerous countries.

The impacts of municipal effluents and biosolids on soil chemical properties and plant growth have been widely studied under unique greenhouse or field conditions involving poplar, eucalyptus, and pine trees (Myers et al. 1996; Roygard et al. 2001). These projects involved site specific characteristics like fine textured soils and arid climates. Crop selection, important for effluent irrigation, can be tailored to suit local conditions and the goals of the program (i.e., water and/or nutrient removal) and help reduce concerns associated with effluents being used to irrigate crops. Table 9.1 and Table 9.2 (Appendix – B) show some of the guidelines and parameters which should be considered when considering effluents as an irrigation source. Crops are known to respond differently to effluent composition; for example, Tesar and Knezek (1982) stated alfalfa (*Medicago sativa* L.) produced higher yields at low application rates (i.e., <5 cm per week) and higher N-demanding crops like corn (*Zea mays* L.), RCG (RCG; *Phalaris arundinacea* L.) and tall fescue (*Festuca arundinacea* Schreb.) yielded higher at higher rates (i.e., 7.5 cm wk^{-1}). The authors stated the end use of the crop should be considered in addition to the role the crop plays in an effluent irrigation program; is the goal nutrient uptake or water use. In the present study for example, if forage use and economic value are important, reed canarygrass (RCG) varieties with lower alkaloid content would be best suited due to their tolerance of local climate and soils in addition to prolonged wet soil conditions in addition they could be sold in a broad range of markets (i.e., feed, biomass, bioproducts, etc). Reed canarygrass, for example, has been studied for its suitability for pulp and paper production (Fennell and Nilsson 2004) and for use in biogas production (Geber 2002).

Land application of pulp or papermill biosolids (Cabral et al. 1998; Hebert and Beaulieu

2002) and wood ash (Mitchell and Black 1995; Vance 1996) produced by the forestry sector have been well studied; few projects have utilized effluents for irrigation (Hansen et al. 1980; Howe and Wagner 1996). Irrigation projects involving pulp mill effluents have involved site specific characteristics like fine textured soils with either arid (<200 mm annual rainfall; Howe and Wagner 1999) or tropical humid climates like India, with >2000 mm annual rainfall (Adisesha et al.1997).

Little research has been conducted to evaluate the use of effluents as supplemental sources of irrigation water in sub-humid climates. Like municipal effluents, pulp mill effluents include N, P, potassium (K^+), sulphate (SO_4^{2-}), Na^+, and Cl^- (Howe and Wagner 1996). Each mineral ion or nutrient may affect plant growth positively or negatively, but also posing environmental problems (i.e., eutrophication, salinization). Hayman and Smith (1979) reported increased soil pH and sodium adsorption ratio (SAR) and decreased alfalfa yields because of irrigation with pulp mill effluent. Hansen et al. (1980) showed effluent applications increased growth of hybrid poplar (HYBP) but also increased concentrations of SO_4^{2-}, Na^+, and Cl^- in groundwater. Irrigation of RCG with saline effluent reduced soil SAR provided increases in Na^+ were accompanied by increases in calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the effluent (Bole et al. 1981) or through applications of gypsum (Howe and Wagner 1996). Accumulated SO_4^{2-} and Cl^- can be flushed from the root zone by precipitation or excess irrigation water (Beltran 1999), while Na can be ameliorated through applications of gypsum or lime (Howe and Wagner 1996). One of the primary concerns of effluent irrigation is long-term site sustainability (Balks et al. 1998; Bond 1998) as the use of saline effluents can lead to negative impacts on soil physical and chemical properties (e.g., salt accumulation within the root zone).

Planning and management taking into consideration factors such as the SAR and electrical conductivity (EC) of the effluent, are required for these irrigation projects, allowing programs to address issues associated with sodium (Na^+), like dispersion, which negatively affects soil structure. Kraft pulp mill effluent (KPME) would be considered 'potentially hazardous' for use in irrigation according to the Food and Agricultural Organization (FAO) water quality standards (Ayers and Westcot 1994). SAR and ECw of the effluent are considered equally important as salinity reduces the potential of Na^+ and other dissolved ions to reduce osmotic potentials (Hayes et al. 1990; Shani and Dudley 2001), to increase dispersion, and to reduce hydraulic conductivity and infiltration (Magesan et al. 1999), thereby impacting long-term sustainability and productivity of irrigated sites. Better information on the guidelines for effluent application can lead to facilities like pulp or paper mills utilizing better quality water (i.e., river water) to supplement or dilute effluents for irrigation programs. Additionally, secondary effluents, like waste activated sludge (WAS), can supplement the nutrient content of effluents.

Patterson et al. (2008) showed increases in both soil sodicity and salinity as a result of effluent applications. Given these increases, the objectives of this study, which built on the former study just referred to, were to compare the effects of municipal tap water (TPW), municipal effluent (ME), Kraft pulp mill waste activated sludge (WAS) and final effluent (KPME) on: (1) the response of RCG and HYBP; (2) the concentration of P, S, Ca, Mg, K, Cl, Na, B, Fe, Mn, and

Zn within plant tissue; and (3) the effect on soil available NO_3, PO_4, K, SO_4, B, Fe, Mn, and Zn.

3.1 MATERIALS AND METHODS

3.1.1 Experimental Design and Treatments

Soil for the study was collected from the Ap horizon (0-20 cm) where a concurrent field study was being conducted; analyses are shown in Table 3.1. The field site was located in the Athabasca region of the boreal forest 200 km northeast of Edmonton, Alberta, Canada (54°55' latitude and 112°52' longitude). The soil was a coarse textured Eluviated Dystric Brunisol. The area where the soils were collected consist of Brunisols, Orthic Gray Luvisols, and Humic Eluviated Gleysols (70% Tawatinaw series, O.GL; 20% Codesa Complex series, B and O.GL; and 10% Mapova series, H.EGL) based on the soil survey of the Tawatinaw map sheet (83-I) (Kjearsgaard 1972). The site slopes west and northwest with 1 to 5% slope and undulating topography. The soils at the study site were classified as Eluviated Dystric Brunisols in the Agriculture Feasibility Study (Table 13.1 to Table 13.5, Appendix – F; Proudfoot 2000). Soils in the area consist primarily of Brunisolic and Luvisolic soils.

The Kraft pulp mill from which the effluent was collected uses aspen (*P. deltoides*) and poplar (*P. balsamifera*) as sources of wood for pulp production. In addition, agriculture, particularly beef cattle production, is common in the region. Due to their adaptability to the soil and climatic conditions of the region, reed canarygrass [RCG; *Phalaris arundinacea* L. cv. Vantage] and one hybrid poplar variety [HYBP; *Populus deltoides* x *P. petrowskyana* L. var. Walker] were selected based on their water use, high nutrient requirements, and known adaptation to the local environment.

The annual precipitation in the region is 503 mm, 67% of which occurs during the growing season from May to September, inclusive (Environment Canada 2005), with moisture deficits often experienced in July and August. The seasonal moisture requirement of a young HYBP plantation was estimated to be 375 mm (Proudfoot 2000). Effluent rates were selected based on this value. An average daily evapotranspiration (ET) rate of 3 mm d^{-1} was chosen as the mid rate of effluent application. This rate was then halved and doubled to provide the other rates (1.5, 3, and 6 mm d^{-1}). Volumes of either effluent or water were adjusted to account for the number of days since the last application (i.e., 96 mL d^{-1} * 2 d = 192 mL). Each treatment had four replications.

Twenty-litre buckets [39 cm x 28.5 cm (inside diameter)] were filled with 30 cm of collected topsoil overlying 6 cm of sand, which facilitated drainage and prevented topsoil loss from the bottom. Fifty milligrams of reed canarygrass (RCG; 700 plants m^{-2}) seed, later thinned to 20 plants pot^{-1}, were added to 1 kg of topsoil and spread evenly over the top of each bucket, covered with 1.5 cm of topsoil and watered for two weeks with 200 mL d^{-1} of distilled water. Reed canarygrass was grown for a total of 121 days with effluent applications beginning at Day 13. The RCG was cut on Day 74 (1st cut) and Day 121 (2nd cut) during the vegetative growth stage.

Styroblocks™ (Block Model 77/125), with 4.2 cm diameter x 11.7 cm deep cavities, were filled with topsoil and then planted with 15-cm HYBP cuttings and watered every 2 days for two weeks with 200 mL of distilled water. Cuttings were transplanted from styroblocks to buckets (one per bucket) on Day 14. Trees were watered on days 16, 18, and 20 with 200 mL of distilled water; effluent applications began on Day 21. The HYBP trees were harvested 86 days later, 107 days after the study began.

Irrigation sources in this experiment consisted of three effluents [a Kraft pulp mill effluent (KPME), a waste activated sludge (WAS), and a municipal waste (ME)], and a control (City of Edmonton tap water, TPW). Treatments were applied to each bucket at rates of 1.5 (i.e., ME-1.5, KPME-1.5, WAS-1.5), 3 (i.e., ME-3, KPME-3, WAS-3), and 6 (i.e., ME-6, KPME-6, WAS-6) mm d^{-1}. This resulted in the application of 11.6, 23.2, and 46.3 L to RCG and 8.2, 16.5, and 32.9 L to HYBP, respectively of each irrigation source. The KPME was collected at the final sampling building prior to effluent being discharged to the river. The WAS was taken from one of the return screens near the screw press at the mill. The municipal effluent (ME) was collected at a sampling location after the effluent had been processed through aerated storage lagoons prior to discharge. Effluents were collected on a weekly basis, transported to the growth chamber, stored for a maximum of 7 d, at room temperature (15 °C), and used the week they were collected. City of Edmonton tap water (TPW) was also used. Waste activated sludge is an effluent slurry, which has undergone a secondary treatment process but contains 3-5% suspended solids which are removed through settling and screw presses to produce KPME and biosolids. The ME and KPME are similar with respect to the lack of suspended solids, while ME and WAS have higher nutrient (i.e., N and P) concentrations relative to KPME. The other key difference between the ME, KPME, and WAS is the higher Na content of the two pulp mill effluents.

Plants were grown under fluorescent lighting in a growth chamber where conditions were a 16:8 hour (light:dark) photoperiod at an air temperature of 15:12 °C (day:night) for four weeks to facilitate plant establishment, after which the temperature was increased to 20:15 °C (day:night). On a weekly basis during the growing period, buckets were progressively shifted from one end of the growth chamber to the other to compensate for potential variations in growth chamber conditions; then moved back to the beginning to begin the process again.

3.1.2 Soil Collection and Analyses

Soil samples were taken when the RCG and HYBP were cut using a 7.5-cm soil auger from two depth increments of 0-10 cm and 10-20 cm from three locations between the centre and circumference of the bucket. Analyses were conducted separately on each depth increment but statistical analyses on the combined set of data (a 0-20 cm depth increment). Three random subsamples taken from the pre-study soil and samples collected at the end of the study were sent for analyses to EnviroTest Laboratories (Edmonton, AB) on the day they were collected. Samples were dried and ground to pass through a 2-mm sieve. Analyses included available nitrate (NO_3), phosphate (PO_4), potassium (K), sulphate (SO_4), boron (B), iron (Fe), manganese (Mn), and zinc (Zn). Soil EC was measured in 1:2 soil:water ratios (Janzen 1993). Soil samples were also analyzed for available NO_3 (Maynard and Kalra 1993) and available SO_4 (Combs et al. 1998) using a 0.01 M $CaCl_2$ solution. A shake extraction was used for NO_3 and SO_4 analyses using deionized water and $CaCl_2$. A reciprocating shaker (Eberbach Model 6000; Eberbach Corporation, Ann Arbor, MI) was used for sample extraction for NO_3 and SO_4 analysis, using deionized water and 0.01 M $CaCl_2$. Soluble NO_3 was analyzed using a Technicon Autoanalyzer (Technicon Instruments Corp., Tarrytown, NY), while SO_4-S was analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES). A Modified Kelowna extraction (NH_4Oac + NHF + HOAc) was used for PO_4 and K analyses; PO_4 was analyzed using a Technicon Autoanalyzer (Technicon Instruments Corp., Tarrytown, NY) and K with a Flame Photometer (Qian et al. 1994). A DTPA extraction was used for the metals Fe, Mn, and Zn, which were then analyzed by ICP-AES (Liang and Karamanos 1993). Boron (B_{HWS}) was extracted in hot water (100°C for 5 min) and analyzed using ICP-AES (Gupta 1993). Soil pH was measured in water and in 0.01 M calcium chloride ($CaCl_2$) suspensions using a 1:2 soil:water ratio (Hendershot et al. 1993). Soil bulk density was determined in the field using Uhland cores (Culley 1993).

3.1.3 Effluent Analyses

Effluent (KPME, WAS, and ME) and water (TPW) samples were analyzed by EnviroTest Laboratories (Edmonton, AB; Table 3.2 and Table 3.3) four times during the study. Effluent and water samples were analyzed for pH (Method 4500-H), EC (Method 2510), alkalinity (Method 2320), trace elements (B, Cu, Fe, and Mn) and ions in solution [SO_4, Ca, K, magnesium (Mg), and sodium (Na); Method 3120 ICP-OES], and Cl by colorimetry (Method 4500) (APHA 1998). Sodium adsorption ratios were adjusted (SAR_{adj}) to account for the high HCO_3^- concentrations (Ayers and Westcot 1994). The deleterious effects of Na^+ are increased when Ca^{2+} and Mg^{2+} precipitate out of solution with CO_3^{2-} and HCO_3^- to for $CaCO_3$ or $MgCO_3$ (Ayers and Westcot 1994; Halliwell et al. 2001).

3.1.4 Plant Growth Measurements

Height of RCG was measured on a weekly basis from the soil surface to the greatest height of the extended leaves. The RCG was cut 10 cm above the soil surface on each of two cuts: the first on Day 74 and the second on Day 121. The remaining 10 cm were collected on Day 121 at the end of the study when soil samples were collected. All samples, including the bottom 10 cm, were dried at 60°C in a drying oven for 72 h and then their biomass determined. Biomass was considered the sum of the dry biomass at each cut and that of the 10 cm collected at the end of the study.

Height and root collar diameter (RCD) were measured on a weekly basis on the HYBP. Height was measured on the main stem from the base to the tip of the main bud. A small caliper was used to measure RCD 2 cm above the base where the stem emerged from the cutting. Trees were harvested after 107 days of effluent application. The stems with leaves removed were cut into sections, dried at 60°C for 72 h, and then weighed to determine their biomass. Stem volume at harvest was calculated using Equation 3.1. Total leaf area (LA) was determined on all leaves by passing each leaf through a Leaf Area Meter (LiCor Model 3100). All leaves were then dried at 60 °C for 72 h and then weighed to determine their biomass. The top two leaves were used for subsequent tissue analyses.

Equation 3.1: Stem Volume = 1/3 * Height * $[(\mathrm{RCD}/2)^2 * \pi]$

3.1.5 Plant Tissue Analyses

Dry tissue samples for both the RCG and HYBP were ground to a fine powder using a small coffee grinder. Samples for tissue analyses were insufficient to complete the full analyses and, as a result, analyses data for tissue N are not presented in this paper. Tissues were then analyzed for P, K, S, Na, Ca, Mg, Cl, B, Mn, and Zn using the method APHA 3120B and APHA 4110B for Cl as outlined for minerals in animal feed (Kalbasi and Tabatabai 1985; Association of Official Analytical Chemists (AOAC) 1990).

Uptake of P, K, S, Ca, Mg, Cl, and Na by RCG was calculated for the 6 mm d^{-1} application rate only by multiplying the RCG biomass (g) of a given cut with the corresponding tissue concentration (mg kg^{-1}) (Equation 3.2). Uptakes from the two cuts were added together to determine total uptake. Uptakes of each element for each treatment (i.e., ME, KPME, and WAS) were then referenced to the corresponding control (TPW) treatment to determine a percent increase or decrease relative to the control. Uptakes at 6 mm d^{-1} were also referenced to the total loading applied through the effluent applications (Table 2.2 and Table 2.3) to determine what percentage of the element applied in the effluent was accounted for by plant uptake. If uptake exceeded 100% of the nutrient applied by the effluent applications, the additional uptake was attributed to nutrients already present in the soil.

Equation 3.2: Nutrient Uptake = Biomass (g) * Nutrient Concentration (mg kg^{-1})

3.1.6 Statistical Analyses

The study utilized a completely randomized design with twelve treatments consisting of combinations of irrigation source (IS) treatments and three application rates (R); each treatment was replicated four times. Results of the soil analyses from the two depth increments (0 to 10 cm and 10 to 20 cm) were averaged together to conduct the statistical analyses. A two-way analysis of variance (ANOVA) was conducted on soil data using irrigation source (IS: TPW, ME, KPME, and WAS), and application rate (1.5, 3, and 6 mm d^{-1}) as main factors with SAS PROC MIXED (SAS Institute 2001). Tissue analyses and biomass measurements for the first and second cuts of RCG were analyzed using repeated measures analyses with SAS PROC MIXED with the main factor cut used as the repeated measure. Repeated measures analyses of the biomass did not include the biomass of the lower 10 cm, which was collected at the second cut. Two-way ANOVAs were used for total RCG biomass, HYPB height, and root collar diameter (RCD) measurements and to analyze soil chemical properties under RCG and HYBP. Statistical differences among means were determined using Tukey's HSD test and all statements of significance were made at P=0.05; statistical differences among means for the main effects [irrigation source (IS); rate (R), and cut (C)] or respective interactions were determined only when the F-value was significant. As a result of insufficient sample, statistical analyses of Cl in the HYBP leaves and of the first RCG cut for the 6 mm d^{-1} control treatment were not conducted. Irrigation source (IS) effects were calculated across the three rates applied for each treatment while rate effects were calculated across the four effluents.

3.2 RESULTS

3.2.1 Irrigation Sources

Waste activated Sludge (WAS) had the highest concentrations for most measured parameters (Table 2.2), especially B, Cu, Fe, Mn, Zn, HCO_3^-, Ca^{2+}, and K^+, followed by KPME, which also had the highest concentration of SO_4^{2-}. Both KPME and WAS had similar concentrations of Cl^- and Na^+. Most parameters for ME were slightly higher than those for TPW, but rarely near the levels of either KPME or WAS, except for B, HCO_3^-, Cl^-, and Mg^{2+}. The KPME and WAS both had higher ECw and SAR than ME and TPW. The ME effluent had moderately high HCO_3^-, ECw, and SAR. Thus increased ECe and SAR and elevated soil concentrations for SO_4^{2-}, Cl^-, Ca^{2+}, K^+, and Na^+ could be expected under KPME and WAS irrigation, and would likely influence the uptake of these elements by the crop.

According to FAO water quality standards (Ayers and Westcot 1994), the KPME used in this study would be considered 'potentially hazardous' for use in irrigation. The SAR_{adj} for the long-term data (1993 to 2002) of 10.5 for the KPME it would lie between the 'potential hazardous' and 'safe' categories. The higher HCO_3^- concentrations in the effluent may result in the formation of $CaCO_3$ and $MgCO_3$ precipitates in the soil, removing Ca and Mg increasing the deleterious effects of Na^+ on soil properties (Ayers and Westcot 1994; Halliwell et al. 2001). According to Steppuhn and Curtin (1993), the effluents used in this study had SAR_{adj} and ECw marginally above that considered suitable as an irrigation source; their use would require monitoring. Effluents used in this study have been approved for use by the appropriate provincial ministry, with monitoring required.

For each of the irrigation sources SAR was adjusted (SAR_{adj}) according to Ayers and Westcot (1994) to account for the high HCO_3^- levels in the Kraft pulp mill effluents. Data for long-term data for KPME and the four irrigation sources used in this experiment were plotted in Piper diagrams (Figure 10.1 to Figure 10.5; Appendix – C). Plotting long-term KPME data in the Piper Diagrams show, the dominant cations being Na^+ + K^+ (~60-75%) in solution followed by Ca^{2+} (~30-35%), and Mg^{2+} at (~5%), while SO_4^{2-} (~45-65%) was the dominant anion in solution followed by HCO_3^- + CO_3^{2-} ranged from (~20-35%), and Cl^- (15-25%) (Figure 10.1). The major cations in solution of the control (TPW) was dominated by Ca^{2+} (~63%) followed by Mg^{2+} (~30%) and Na^+ + K^+ (~7%) in solution, while anions were dominated by SO_4^{2-} (~37%), HCO_3^- + CO_3^{2-} (60%), and Cl^- (~3%) in solution (Figure 10.2). For the municipal effluent (ME), dominant cations in solution were Na^+ + K^+ (~50%), followed by Ca^{2+} (~30%) and Mg^{+2} (~20%) in solution, while anions were dominated by HCO_3^- + CO_3^{2-} (~63%), Cl^- (~22%), and then SO_4^{2-} (~15%) (Figure 10.3). Data collected from this growth chamber experiment for KPME (Figure 10.4) were comparable to the long-term values. For the waste activated sludge (WAS), dominant cations in solution were Na^+ (~70%), followed by Ca^{2+} (~23%) and Mg^{+2} (~7%), while anions were dominated by HCO_3^- + CO_3^{2-} (50%), SO_4^{2-} (35%), and Cl^- (15%) (Figure 10.5).

3.2.2 Reed Canarygrass and Poplar Growth

For RCG biomass, three-way interaction (ISxRxC) effects were significant between the first (Figure 3.1A) and second cuts (Figure 3.1B). Total biomass (Figure 3.1C) increased significantly with increasing application rate and increased slightly with effluent treatments relative to the control at the 6 mm d^{-1} rate. Except for Cut 1, the biomasses of RCG of ME-6, KPME-6, and WAS-6 were significantly greater than that of TPW-6 (Figure 3.1A and B). This could have been due to residual nutrients (e.g., N) already present in the soil for the first portion of the experiment. The effluents were providing enough water and nutrients at all rates for comparable biomass between the two cuts. Reed canarygrass height (data not shown) increased significantly with rate in both the first and second cuts.

Application rate significantly affected HYBP root collar diameter (RCD), height, stem volume, dry weight, and leaf area (LA) by the end of the study (Figure 3.2). For HYBP, RCD, LA, and biomass showed significant ISxR interactions. The RCDs of trees irrigated with WAS were slightly greater than those irrigated with KPME at all three rates, with the same trend observed for height. Trees irrigated with TPW and ME were taller and had greater RCDs at all three rates than both KPME and WAS, except for the 1.5 mm d^{-1} ME treatment. At the lower application rate, all three effluent treatments had stem volumes lower than that of TPW at the same rate. However, only the stem volume of KPME or WAS irrigated trees was lower than TPW at 3 mm d^{-1}, while none of the effluent treatments had stem volumes less than TPW at the 6 mm d^{-1} rate. Across effluents, LAs of HYBP increased significantly with application rate (Figure 3.2). The incremental increase in LA between the KPME-3 and KPME-6 treatments was lower than those in the corresponding TPW, ME, or WAS treatments. Lower LAs may have been the result of leaf drop that occurred in only KPME-6, visually observed, and resulting in the similar trend, which was observed in the biomass results.

3.2.3 Tissue Analyses and Nutrient concentration

Tissue P concentrations in RCG were affected by R and irrigation source-by-cut (ISxC) interactions (Table 3.4). Increases in tissue P in the effluent treatments were consistent with the P concentrations within these effluents (Table 3.4). Tissue P increased with increasing application rate, except for the 2nd cut irrigated with KPME and ranged from 0.12 to 0.26%. Among rates, tissue P for 6 mm d^{-1} was significantly greater than those for the two lower application rates; no significant differences were measured in tissue P between the 1.5 and 3 mm d^{-1} rates. Across application rates, tissue P concentration were significantly greater in WAS than in TPW, KPME, and ME (Table 3). Uptake of P by RCG accounted for 63% of P applied in ME, 100% of P applied in KPME, and 62% of P applied in WAS. Phosphorus within HYBP tissue also showed significant differences among rates (data not shown).

The amount of SO_4 applied with each irrigation was comparable between TPW and ME, while irrigation with KPME and WAS applied 8 to 10 times more SO_4 compared to that of TPW (Table 2). Tissue S in RCG was significantly greater within TWP-6 compared to the other treatments; no significant differences were measured among the other treatments (Table 3.4). Tissue S concentration ranged between 0.22 and 0.50% at 6 mm d^{-1}. Reductions of 35, 43, and 25% were measured compared to TPW for ME, KPME, and WAS, respectively. At 6 mm d^{-1} uptake of S by RCG accounted for 4.6% of the SO_4 applied by ME, 0.41% applied by KPME, and 0.74% applied in WAS. In HYPB, tissue concentration of S was significantly affected by rate where 3 and 6 mm d^{-1} resulted in tissue S significantly greater than that for 1.5 mm d^{-1} (data not shown).

Tissue Ca concentrations in RCG were significantly affected by the ISxRxC interaction and decreased with increasing rate, except for WAS in the first cut and TPW in the second cut (Table 3.4) and decreased between the first and second cut, which was attributed to lower Ca availability. Calcium concentrations in RCG ranged from 0.52 to 0.84%, with uptake by RCG accounting for 14% of that applied through ME, 4.8% of that applied through KPME, and 6.1% of that applied by WAS. In HYBP tissue Ca was significantly increased with WAS compared to TWP; no significant differences were measured among ME, KPME, and WAS (data not shown).

Magnesium concentrations in RCG ranged from 0.22 to 0.49%. Across irrigation sources (IS), concentration of Mg in RCG tissue tended to increase with increasing application rate; a trend opposite to that observed for K in the same tissues. In HYBP leaves, tissue Mg was lower in ME, KPME, and WAS compared to TPW; with significant differences only between TPW and KPME (data not shown). Across application rates in HYBP tissue, tissue Mg was significantly lower in KPME compared to TPW, opposite that measured for K concentrations in the same tissues.

Sodium concentrations in soil irrigated with KPME and WAS were 5 times greater than that in ME and 46 times greater than that in TPW (Table 3.2). In RCG, tissue Na was affected by ISxRxC interactions (Table 3.4). Tissue Na was comparable between cuts for TPW, ME, and KPME while it increased significantly from the first cut to the second in the 1.5 mm d^{-1} WAS (Table 3.4). Uptake of Na by RCG accounted for only 1.4% of the Na applied by ME, 0.63% applied by KPME, and 0.95% applied through WAS. Sodium in RCG and HYBP was significantly greater in WAS compared to TPW, ME, and KPME (data for HYBP is not shown).

Potassium concentration of RCG tissue was affected by application rate and ISxC interactions (Table 3.4) with concentrations decreasing with increasing application rate. Concentrations of K in the effluents were greatest in the pulp mill effluents followed by ME, and then TPW; a similar trend was found in the tissue analyses. At 6 mm d^{-1} uptake of K, by RCG, accounted for 100% of the K applied by ME, 67% of that applied by KPME, and 59% of that applied by WAS. Tissue K concentration in HYBP tissue were significantly greater in KPME and WAS than in TPW (data not shown); no significant differences were measured between the ME and TPW, KPME, and WAS treatments.

Chloride concentrations were higher in the pulp mill effluents followed by the municipal effluent and then the control. Reed canarygrass tissue Cl ranged from 0.5 to 2.4% and 0.4 to 2.3% in the first and second cuts, respectively (Table 3.4). In ME and WAS, tissue Cl increased with increasing rate; but not in KPME. At 6 mm d^{-1} uptake by RCG accounted for 33, 14, and 15%, respectively, of the Cl applied by ME, KPME, and WAS.

Concentrations of B in the effluents were greatest in WAS and ME followed by KPME and then TPW. Concentration of B in RCG tissue was significantly affected by ISxRxC interactions (Table 3.4). At 6 mm d^{-1} B uptake by RCG only accounted for 9.4% of B applied by ME and decreased to 2.3% of B applied in WAS. No significant differences were measured in the tissue concentrations of B of the HYBP because of ISxR interactions (data not shown). In RCG tissue, Mn was affected by all main factors and interactions, except rate and rate-by-cut (RxC) and was significantly, greater in WAS treatments compared to TPW, ME, and KPME (Table 3.4). Tissue Mn in RCG tissue was significantly greater in plants irrigated with WAS than those irrigated with TPW, ME, and KPME. Zinc concentration in RCG tissue showed significant ISxRxC interaction effects (Table 3.4). No significant differences were measured in concentrations of Zn in the second cut. No significant differences in leaf concentrations of Zn were measured in HYBP as a result of Irrigation source, application rate, or the ISxR interaction (data not shown).

3.2.4 Available Nutrients and Trace Elements

Soil nutrient (i.e., N, P, K, and S) and trace element (i.e., B, Fe, Mn, and Zn) loadings resulting from effluent and control treatments in this study were similar to those of other studies (Campbell 1983; Howe and Wagner 1996).

Available NO_3 under RCG (Table 3.5) was significantly affected by an irrigation source-by-rate interaction (ISxR), while only rate affected available NO_3 under HYBP (Table 3.6). At the end of the study, available NO_3 levels decreased with increasing rate, with highest levels measured at the lowest rate for ME and WAS. This was not observed in soils planted with HYPB; the greatest available NO_3 levels occurred at the 3 mm d^{-1} rate at the end of the study for both water and effluent. For both RCG (Table 3.5) and HYPB (Table 3.6), available PO_4 and K concentrations were affected by effluent applications. Soils irrigated with WAS had significantly greater levels of available PO_4 and K than those measured in soils irrigated with TPW, ME, and KPME. Available PO_4 concentrations in soils irrigated with WAS increased with increasing rate; this was not observed in TPW, ME, or KPME. With the exception of HYPB irrigated with KPME and WAS and RCG irrigated with ME, plant available levels of K decreased with increasing rate. Irrigation source-by-rate (ISxR) significant interaction effects occurred for plant available SO_4 concentrations in soils with either RCG (Table 3.5) or HYPB (Table 3.6). Waste activated sludge (WAS) and KPME resulted in significantly greater SO_4 concentrations in soils compared to TPW and ME for RCG (Table 3.5) and HYBP (Table 3.6). This would be expected as WAS and KPME effluents have much greater concentrations of SO_4. The abnormally high concentrations of available SO_4 under HYBP for the TPW control were verified and confirmed with the laboratory.

Available B concentrations in RCG showed only an irrigation source (IS) effect and were significantly greater in ME and WAS treatments compared to KPME and TPW (Table 3.5). Similar observations were made with HYBP (Table 3.6) where concentrations in soils irrigated with WAS were significantly greater than those in TPW, ME, and KPME, but all were lower than the Canadian Council of Ministers of the Environment (CCME 2006) criterion (2 mg kg^{-1}; hot water soluble boron). The ISxR interaction was significant for plant available Fe, which was generally lower under RCG with WAS (Table 3.5). The same observation was made for HYBP (Table 3.6) irrigated with WAS and KPME. Plant available Mn and Zn had significant effluent effects for both RCG (Table 3.5) and HYBP (Table 3.6). Available Mn and Zn concentrations in soils planted with RCG or HYBP were significantly greater in those irrigated with WAS compared to TPW, ME, and KPME.

3.3 DISCUSSION

Water, not nutrient, availability was the most limiting factor as biomass increases were observed for all four irrigation treatments with increasing rate. However, given the growth response to irrigation with TPW, growth observed under effluent irrigated treatments may have been confounded by the amount of water supplied. Across rates, application of KPME and WAS to RCG resulted in biomass comparable to or greater than that in TPW. When irrigated with various types of effluent had significantly increased biomass of other crops, such as tall fescue (*Festuca arundinacea* Schreb.) (King 1982), orchardgrass (*Dactylis glomerata* L.) (Palazzo 1981), alfalfa (*Medicago sativa* L.), ryegrass (*Lolium perenne* L.), and white clover (*Trifolium repens* L.) (Sakadevan et al. 2000). However, increasing effluent application rate to achieve higher yields needs to be balanced with increases in soil salinity, sodicity, or increased pH (Bie et al. 2004). Combining effluents with better quality water sources may be one option to increase the amount of water applied and minimize adverse effects on soil chemical properties. Both KPME and WAS tended to have more effect on soluble Na, Ca, K, SO_4, and Mg than did either ME or TPW (Table 3.7). Irrigation with saline or sodic effluents, like KPME or WAS, will likely result in the salinization and/or sodification of the rooting zone limiting plant productivity unless properly managed or development of some type of guidelines for their use. For example, reduced osmotic potential in soils irrigated with KPME may have caused the trees under water stress as a result of high salinity, Na, or HCO_3 (Bie et al. 2004).

At the higher application rates, trees irrigated with KPME dropped their lower leaves, a sign of water stress. Subsequently these trees were smaller in stature with less biomass compared to trees irrigated with TPW, ME, or WAS. Leaf drop occurs to minimize water loss through transpiration. While leaf drop was not observed in trees irrigated with WAS, the increased water and nutrients applied in the WAS at the 6 mm d^{-1} rate may have provided some leaching and helped improve the tolerance of the trees to the saline conditions. Increasing rates also increased stem volume relative to the TPW control; at lower rates all effluent treatments had stem volumes equivalent to or less than the control. As rates were increased only the Kraft effluents had stem volumes lower than the control at 3 mm d^{-1}, while none of the effluent treatments had volumes lower than the control at 6 mm d^{-1}. While the study indicated rate as a possible limiting factor, it is more likely the supply of water limited growth. However, without further testing, this is only speculation. Additional amendments like gypsum or lime could be applied to ameliorate the increased Na applied; however, the increased pH caused by both the effluent and lime may also negatively affect the growth of pH sensitive crops like poplar (Dickman and Stewart 1983), but favor forages like reed canarygrass.

Tissue P increased because of irrigating with ME and WAS consistent with the chemistry of these two effluents; dissolved P concentrations were the highest in the ME and WAS effluents (Table 2). While an increase in tissue P was measured in the highest TPW rate, its concentration was still less than those measured in the lowest rates of ME and WAS. Sakadevan et al. (2000) reported P in mixed ryegrass and white clover pasture was significantly greater under recycled water irrigation compared to control and fertilized treatments, a trend observed by this study with ME and WAS effluents.

Concentrations of S, Ca, and K in tissues were greatest in the treatments irrigated with pulp mill effluents followed by ME and TPW, while Mg concentrations in ME were lower than those in WAS but greater than in both KPME and TPW (Table 2.2). When compared to TPW, decreases in nutrient uptake by RCG was measured for S, Ca, and Mg when irrigated with KPME, and S when irrigated with ME at application rates of 3 and 6 mm d^{-1} and K, S, Ca, and Mg when irrigated with 1.5 mm d^{-1} WAS and S at 6 mm d^{-1} WAS. The decrease in S removal by RCG was unexpected, especially given the concentration of SO_4 within the KPME and WAS effluents. This decrease may be due to nutrient imbalances or deficiencies within the soil (e.g., N, Table 3.5), which were limiting S uptake, but would require further study.

Concentration of K in RCG was greatest for WAS followed closely by those with KPME and ME; additional N applied through WAS may have facilitated greater K uptake by RCG since N and K positively influence the uptake of each other (Marschner 2002). The increased uptake of K by these treatments may also be due to physiological processes within the plant as K ions are important for water relations within the plant (Marschner 2002). Palazzo (1981) stated plant uptake of N, P, and K increased with each cut and suggested the period until the first cut could be used for higher application rates to established forage stands. Decreasing concentrations of P and K measured in this study between cuts may be due to the development of nutrient limitations (e.g., N) or nutrient imbalances. For example, higher soil K loadings caused by KPME and WAS, coupled with precipitation of Ca and Mg by HCO_3, could be responsible for the diminished uptake of Ca and Mg by RCG relative to TPW.

Reductions in Ca and K concentrations within the tissues combined with increases in Na may have disrupted cellular function and structure within the plant like ion transport, osmotic regulation, and cell wall integrity (Marschner 2002). These functions can be impaired through reductions in Ca, Mg, and K as Ca, Mg, and K are important for plant nutrition. However, in soil solution they become competitive, influencing the uptake of each other. Magnesium uptake is strongly depressed by the presence of cations such as Ca^{2+} and K^{+} (Marschner 2002). The lower tissue Mg in KPME treatments measured in this study relative to TPW can be due to the competitive effects K and Ca would have on Mg uptake, consistent with the antagonistic relationship these elements have with respect to plant uptake (Marschner 2002). According to Marschner (2002) for mineral nutrients, such as K^{+}, Ca^{2+}, and Mg^{2+} that are taken up as cations, binding strength, at cell wall exchange sites, is smaller for Mg^{2+} because of the degree of hydration compared to K^{+} or Ca^{2+}. As a result, K^{+} or Ca^{2+} compete and depress the rate of Mg^{2+} uptake by the plant. Calcium helps strengthen cell walls and plays an important role as a secondary messenger for the growth and development of the plant. Potassium is important for photosynthesis and acts in the osmoregulation and water movement within the plant.

Both KPME and WAS contained similar concentrations of Na but WAS, like ME, also contained higher concentrations of nutrients such as N and P. The nutrient effects in the case of WAS may have overshadowed the salinity issues caused by KPME additions (i.e., leaf drop). As a result more Na was taken up with WAS compared to KPME. Howe and Wagner (1996) stated Na uptake by poplar accounted for only 0.002% of the Na input by effluent; greater stem biomass was associated with lower tissue Na. They suggested that addition of calcium amendments such as lime or gypsum may increase plant tolerance to sodic effluent irrigation. Hayes et al. (1990) found no significant differences in soil K in effluent treatments compared to a potable water control. Mancino and Pepper (1992) measured decreases in soil K in plots irrigated with potable water while waste activated sludge irrigated plots maintained original concentrations.

The increased tissue Cl measured in ME and WAS relative to KPME could be due to the additional N applied by these two effluents that aided the growth of the RCG. Renault et al. (1999) observed significantly higher P, Ca, Mg, Na, K, and B in HYBP seedlings grown in composite tailings water with elevated Na, SO_4, and Cl compared with deionized water, indicating uptake of the applied Na, SO_4, and Cl by the HYBP. The results were similar to those of this study where, HYBP irrigated with effluent had elevated foliar Na, SO_4, and Cl. The decreasing concentrations of NO_3 and K, measured in the current study, with increasing application rate may be due to a dilution effect caused by higher biomass (i.e., more tissue) for these irrigation rates.

Concentrations of B in plant tissue were within acceptable ranges (McKenzie 1992) for all samples, including the WAS-1.5 mm d^{-1} for the second cut. Concentration of B in RCG tissue tended to decrease with increasing rate, except for the second cut irrigated with TPW and KPME. Again, this could be attributed to a dilution effect caused by increased dry matter and reduced availability due to removal of B by the first cut of RCG. This was also observed for Mn, except for the second cut of RCG irrigated with KPME and WAS. Accumulation on the surface of plant tissue could be responsible for high Mn concentrations, especially in tissue samples from WAS since plant tissues in this study were not rinsed before analyses were conducted. King (1982) suggested Mn in unwashed fescue was higher in effluent treatments but later attributed this to solids adhering to plant surfaces and not to plant uptake. While this is speculation, it this does not explain why the same trend was measured in the leaf tissue of HYBP (data not shown) since irrigation source applications were made to the base of the tree and not sprayed. It is unlikely solids were responsible for increased Mn concentrations measured in the HYBP leaf tissue. The top two leaves of the HYBP were used for analyses and would not have been exposed to any of the WAS applied during the course of the study. No specific trends were observed for tissue Zn of the RCG in either cut.

Plant available PO_4 was significantly greater with WAS compared to TPW, ME, and KPME (Table 3.5), consistent with King (1982) who also measured elevated soil PO_4, K, Ca, and Mg due to fiberboard effluents. They also observed no significant differences between effluents and the control for Na. Should accumulations of PO_4 and SO_4 occur, in soils, under field conditions in effluent irrigation projects, there is potential for groundwater contamination by PO_4 and SO_4, considering their potential for leaching, especially in coarse textured soils like in this study. The higher B concentration in RCG irrigated with ME was most likely associated with sodium borate, a common ingredient in household detergents used for washing clothes (Asano 1987). Soil concentrations of B under RCG and HYBP were under the CCME limit (2 mg kg^{-1}; CCME, 2006). These concentrations were not likely negatively affecting the growth of either RCG or HYBP. Available Mn decreased with increasing rate for TPW, ME, and KPME with RCG or HYPB. The trend could be due to increased soil pH measured within these treatments, but could also be due to increased uptake (Patterson et al. 2008). Availability of Fe and Mn within the soil decreases with increasing soil pH (Havlin et al. 1999). Mancino and Pepper (1992) stated Mn accumulated in soils irrigated with secondary municipal effluents while Zn in their study was significantly lower in effluent irrigated plots and remained unchanged in plots irrigated with potable water. The authors attributed changes to greater uptake rates by turf grass. In a study by Hayes et al. (1990) soil Mn increased and Zn decreased with effluent irrigation.

In this study, the application of WAS resulted in the greatest concentration of soil NO_3, PO_4, K, SO_4, B, Mn, and Zn. The WAS treatments also resulted in increased soluble Na^+, Ca^{2+}, and K^+ in the soil and elevated plant tissue concentrations of N, P, K, Ca, Na, Mn, and Zn. Uptake of S was influenced more by TPW than by ME, KPME, or WAS. The generalized trends throughout this study and one conducted previously (Patterson et al. 2008) indicated WAS and ME had more of an influence on plant available N, P, K, B, Fe, Mn, and Zn than KPME and TPW (Table 3.7), while WAS had greater or comparable impacts on soils or plant tissues than ME.

3.4 CONCLUSIONS

Water was the limiting factor for the growth of both the reed canarygrass and hybrid poplar. Increasing the rate, through either additional water or effluent applications, may further increase growth, but consideration must be made of the effects these increases may have on soil chemical properties.

Increasing the application rate of the irrigation sources increased RCG dry biomass and HYBP height, leaf area, and dry biomass. Relative to TPW, irrigation with ME increased plant available concentrations of S and B; WAS increased soil extractable concentrations of N, P, K, B, Mn, and Zn and irrigation with KPME increased available SO_4. Soil available B under WAS treatments only slightly Exceeded criteria but not to a point which adversely affected crop growth. ME and WAS were comparable in their effects on plant growth, soil and tissue analyses. Hence ME and WAS could be used to increase the nutrient content of KPME benefitting plant growth. However, the use of KPME or WAS as sources of irrigation water will likely be limited unless Na concentration in the effluent can be reduced, or Na loadings in the soil managed through soil amendments like gypsum or lime for low pH soils. Determination of application rates based on effluent chemical characteristics will be essential; however; the effects of over irrigation, annual precipitation, or application of Ca- or Mg-based materials such as lime or gypsum to maintain productivity and site sustainability need to be addressed. More information is needed, however, on the impacts on soil dispersion, nutrient accumulations, leaching and subsequent effects on groundwater in order to understand the long term impacts and potential site sustainability of managing saline or sodic effluents via effluent irrigation projects.

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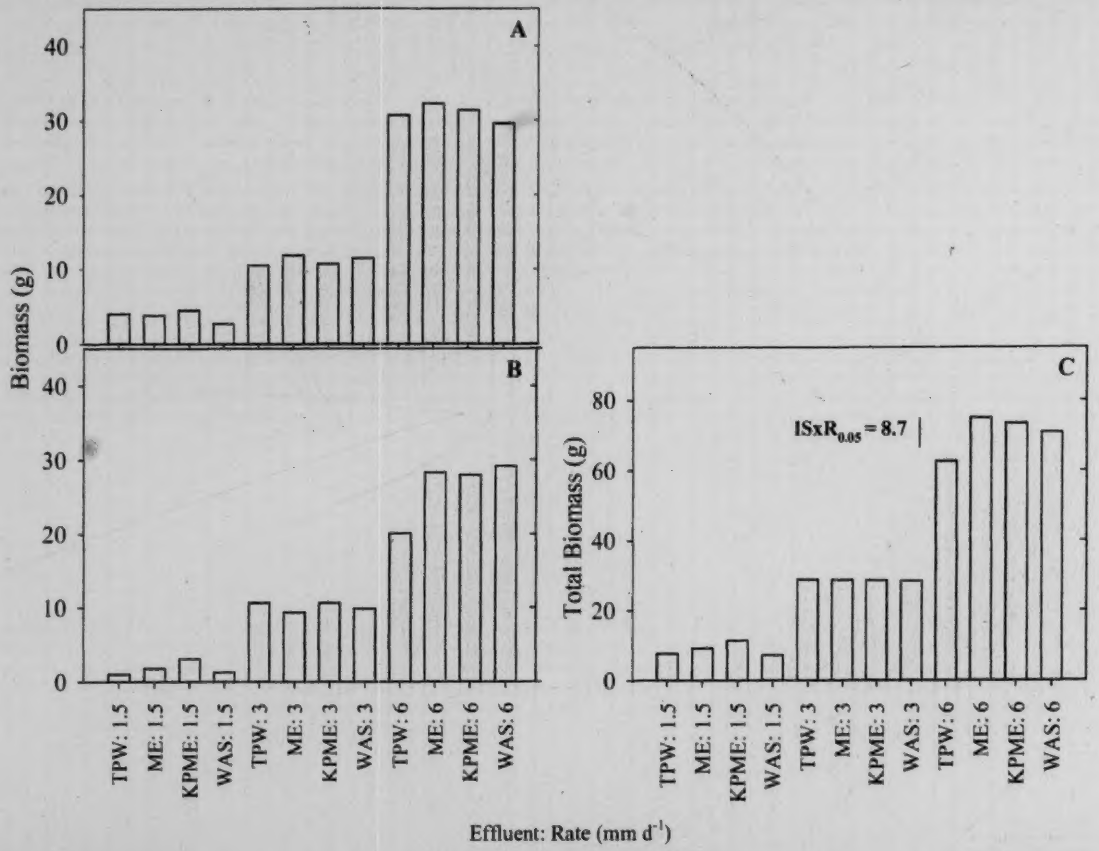

Figure 3.1. Reed canarygrass biomass for the 1st cut (A), 2nd cut (B), and total biomass (C) after 108 days of irrigation source applications. Tukey's $HSD_{0.05}$ values were used to separate the significant irrigation source-by-rate ($ISxR_{0.05}$) interaction measured in the RCG total biomass. Numbers along horizontal axis represent rates in mm d^{-1}. Between the 1st (A) and 2nd cut (B), significant IS ($HSD_{0.05}$=1.9), R ($HSD_{0.05}$=1.5), cut (C; $HSD_{0.05}$=1.0), and RxC ($HSD_{0.05}$=2.7) interactions were observed.

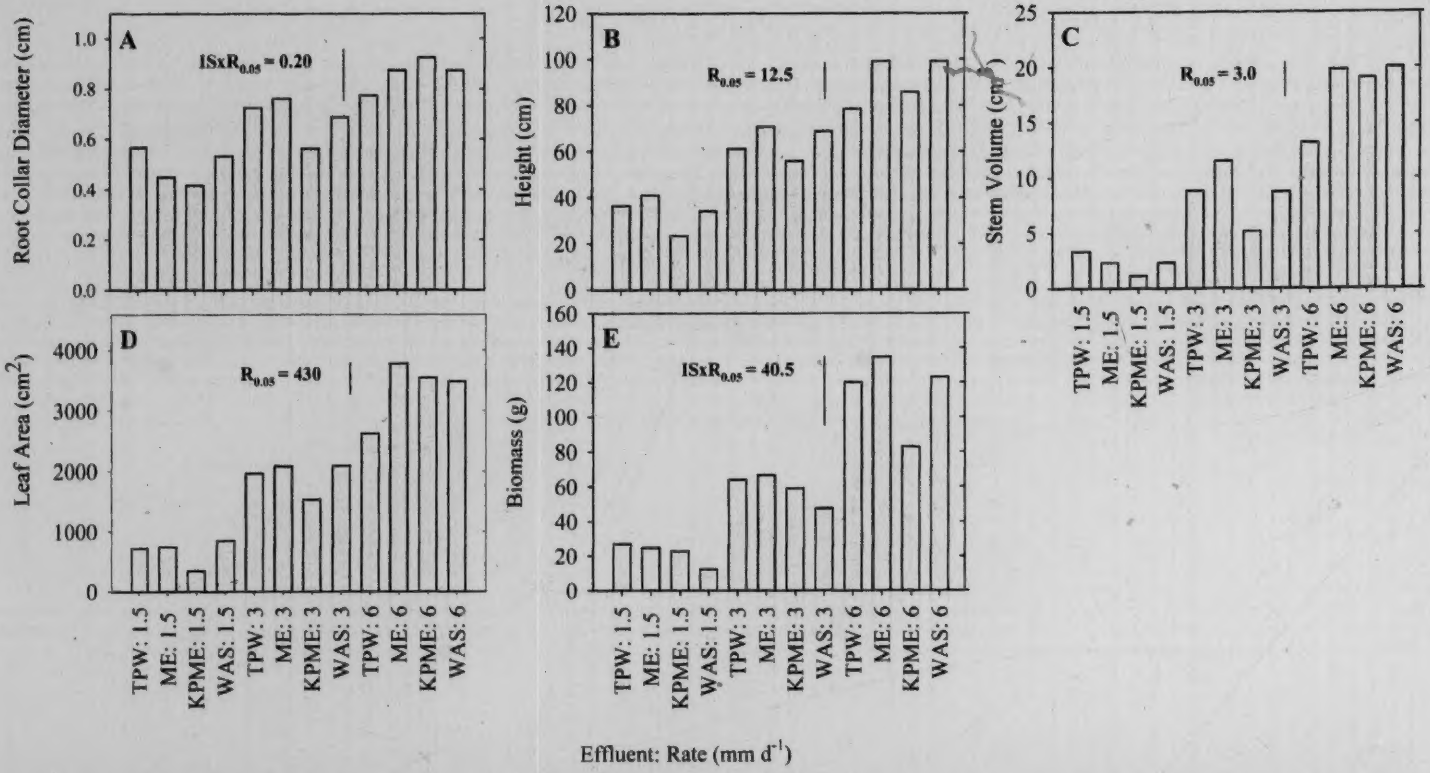

Figure 3.2. Average root collar diameter (RCD; A), height (B), stem volume (C), leaf area (D), and biomass (E) of HYBP after 86 days of control (TPW), municipal effluent (ME) and Kraft pulp mill effluent (KPME & WAS) applications. Means were separated using Tukey's HSD$_{0.05}$ shown for significant rate (R$_{0.05}$) and irrigation source-by-rate (ISxR$_{0.05}$) effects. Significant rate effects were observed for RCD, height, stem volume, LA, and biomass with the following trend observed 6 > 3 > 1.5 mm d^{-1} (>, indicates a significant increase). Numbers along horizontal axis represent rates in mm d^{-1}.

Table 3.1. Mean (n=3) values (± S.E.) of selected soil chemical and physical characteristics

Characteristic		Average
Bulk Density (Mg m^{-3})		1.12
[Z] PAW (cm^3 cm^{-3})		0.28
Texture		Loam
	Sand (g kg^{-1})	35.3 ± 0.7
	Silt (g kg^{-1})	44.3 ± 0.9
	Clay (g kg^{-1})	20.3 ± 0.3
pH		5.9 ± 0.1
[Y] EC (dS m^{-1})		1.8 ± 0.2
[X] CEC (cmol kg^{-1})		20.1 ± 0.2
Saturation (%)		45.7 ± 0.7
[W] SAR		0.3 ± 0.0
Ca (mg kg^{-1})		119.8 ± 15.3
K (mg kg^{-1})		2.2 ± 0.2
Mg (mg kg^{-1})		24.1 ± 2.8
Na (mg kg^{-1})		9.6 ± 0.4
Cl (mg kg^{-1})		13.2 ± 1.7
SO_4 (mg kg^{-1})		26.2 ± 0.9

[Z] PAW – Plant Available Water: Pressure levels chosen for the loam textured Eluviated Dystric Brunisol soil for field capacity and wilting point were 10 kPa and 1500 kPa, respectively

[Y] Electrical Conductivity

[X] Cation exchange Capacity

[W] Sodium Adsorption Ratio

Table 3.2. Selected mean (n=4) chemical and nutrient properties of control (TPW), municipal effluent (ME), Kraft pulp mill effluent (KPME) and waste activated sludge (WAS) irrigation sources used in this growth chamber study taken from Patterson et al. (2008)

		Effluent Concentrations			
[Z] Treatment		TPW	ME	KPME	WAS
pH	pH	7.8	7.5	7.7	7.2
[Y] ECw	dS m^{-1}	0.37	1.06	2.52	2.87
[X] TDS	mg L^{-1}	0.2	0.5	1.7	1.8
		---------------------------- mg L^{-1} ----------------------------			
[W] TKN	mg L^{-1}	0.4	42.7	1.8	299.0
[V] Diss-P	mg L^{-1}	0.02	3.5	1.7	4.7
B	mg L^{-1}	0.02	0.27	0.05	0.9
Cu	mg L^{-1}	0.05	0.03	0.01	0.3
Fe	mg L^{-1}	0.07	0.36	0.17	34.5
Mn	mg L^{-1}	0.01	0.27	0.18	66.5
Zn	mg L^{-1}	0.03	0.09	0.06	12.5
HCO_3	mg L^{-1}	139.5	412.5	483.8	925.5
SO_4	mg L^{-1}	66.9	73.6	724.3	529.8
Cl	mg L^{-1}	4.5	91.0	164.3	166.0
Ca	mg L^{-1}	45.3	45.3	56.3	113.7
K	mg L^{-1}	1.0	15.7	45.1	62.6
Mg	mg L^{-1}	13.2	21.0	18.2	24.3
Na	mg L^{-1}	9.5	90.8	435.0	439.3
[U] SAR	mg L^{-1}	0.5	3.7	14.1	12.6
[T] SAR_{adj}	mg L^{-1}	0.3	3.3	14.5	14.5

[Z] TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge
[Y] EC - Electrical conductivity of irrigation source
[X] TDS – Total Dissolved Solids
[W] TKN – Total Kjeldahl Nitrogen
[V] Diss-P - Dissolved Phosphorus
[U] SAR - Sodium Adsorption Ratio
[T] SAR_{adj} – Adjusted SAR (Ayers and Westcot 1994)

Table 3.3. Total soil loadings (mg) due to control (TPW), municipal effluent (ME), Kraft pulp mill effluent (KPME) and waste activated sludge (WAS) irrigation sources used in the study irrigation source applications at 6 mm d^{-1} for soils planted with RCG or HYBP used in this growth chamber study taken from Patterson et al. (2008)

		Amount Applied (mg pot^{-1})							
		Reed Canarygrass (41.3 L Applied)				-- Hybrid Poplar (32.9 L Applied) --			
[Z] Treatment		TPW	ME	KPME	WAS	TPW	ME	KPME	WAS
		---------- mg ----------				---------- mg ----------			
[W] TKN	mg L^{-1}	17.0	1 764	74.3	12 349	13.0	1 405	59.2	9 837
[V] Diss-P	mg L^{-1}	0.8	143	70	194	0.7	114	56	155
B	mg L^{-1}	0.8	11.2	2.1	35.1	0.7	8.9	1.6	28.0
Cu	mg L^{-1}	2.1	1.2	0.4	10	1.6	1.0	0.3	8.2
Fe	mg L^{-1}	2.9	15	7.0	1 425	2.3	11.8	5.6	1 135
Mn	mg L^{-1}	0.4	11	7.4	2 748	0.3	8.9	5.9	2 189
Zn	mg L^{-1}	1.2	3.7	2.5	517	1.0	3.0	2.0	412
HCO_3	mg L^{-1}	5 761	17 036	19 981	38 223	4 590	13 571	15 917	30 449
SO_4	mg L^{-1}	2 763	3 040	29 914	21 881	2 201	2 421	23 829	17 430
Cl	mg L^{-1}	186	3 758	6 786	6 856	148	2 994	5 405	5 461
Ca	mg L^{-1}	142.8	1 871	2 325	4 696	5 898	1 490	1 852	3 741
K	mg L^{-1}	41	648	1 863	2 585	33	517	1 484	2 060
Mg	mg L^{-1}	545	867	752	1 004	434	691	599	799
Na	mg L^{-1}	392	3 750	17 966	18 143	313	2 987	14 312	14 453
[U] SAR	mg L^{-1}								
[T] SAR$_{adj}$	mg L^{-1}								

[Z] TPW – Tap water control; ME – Municipal Effluent; KPME – Kraft Pulp Mill Effluent; WAS – Kraft Pulp Mill Waste Activated Sludge

[Y] EC - Electrical conductivity of irrigation source

[X] TDS – Total Dissolved Solids

[W] TKN – Total Kjeldahl Nitrogen

[V] Diss-P - Dissolved Phosphorus

[U] SAR - Sodium Adsorption Ratio

[T] SAR$_{adj}$ – Adjusted SAR (Ayers and Westcot 1994)

Table 3.4. Mean tissue (n=4) concentrations of P, S, Ca, Mg, K, Cl, Na, B, Mn, and Zn in RCG after irrigation with control (TPW), municipal effluent (ME), Kraft pulp mill effluent (KPME) and waste activated sludge (WAS) after 108 days of irrigation source applications

	P	S	Ca	Mg	Na	K	Cl	B	Mn	Zn
[Z] Irrigat. Source: Rate	----------	----------	----------	%	----------	----------	----------	--------	mg kg^{-1}	--------
1st Cut										
TPW: 1.5 mm day^{-1}	0.12	0.32	0.77	0.24	0.08	2.5	0.5	24.3	71.6	52.2
TPW: 3 mm day^{-1}	0.12	0.35	0.63	0.29	0.05	2.3	0.5	15.6	48.5	58.4
TPW: 6 mm day^{-1}	0.16	0.50	0.52	0.34	0.09	1.9	n/a	14.8	25.9	35,3
ME: 1.5 mm day^{-1}	0.17	0.31	0.82	0.28	0.07	2.7	1.5	30.6	72.7	63.9
ME: 3 mm day^{-1}	0.17	0.29	0.75	0.39	0.07	2.5	2.2	25.5	61.5	57.4
ME: 6 mm day^{-1}	0.20	0.29	0.67	0.49	0.10	2.3	2.4	22.7	33.6	47.1
KPME: 1.5 mm day^{-1}	0.15	0.27	0.58	0.24	0.13	2.9	2.0	18.9	73.2	56.3
KPME: 3 mm day^{-1}	0.15	0.28	0.53	0.28	0.23	2.8	2.3	17.3	70.8	63.8
KPME: 6 mm day^{-1}	0.15	0.25	0.43	0.27	0.23	2.4	1.7	14.9	54.0	42.2
WAS: 1.5 mm day^{-1}	0.19	0.32	0.73	0.25	0.33	3.1	1.0	22.6	194.3	73.1
WAS: 3 mm day^{-1}	0.23	0.34	0.81	0.32	0.32	2.9	1.4	21.9	285.9	100.7
WAS: 6 mm day^{-1}	0.26	0.37	0.84	0.34	0.37	2.8	1.9	18.9	335.5	114.7
2nd Cut										
TPW: 1.5 mm day^{-1}	0.12	0.24	0.58	0.23	0.06	2.9	0.9	15.6	41.9	77.7
TPW: 3 mm day^{-1}	0.13	0.26	0.60	0.29	0.06	2.9	1.2	14.6	29.0	58.7
TPW: 6 mm day^{-1}	0.15	0.44	0.52	0.32	0.07	1.9	0.4	16.5	25.5	42.6
ME: 1.5 mm day^{-1}	0.12	0.23	0.60	0.24	0.06	2.9	1.5	16.0	40.8	75.6
ME: 3 mm day^{-1}	0.12	0.22	0.58	0.27	0.07	2.6	1.8	15.3	33.1	71.4
ME: 6 mm day^{-1}	0.13	0.23	0.54	0.30	0.11	2.5	2.1	15.0	23.2	63.5
KPME: 1.5 mm day^{-1}	0.14	0.24	0.57	0.22	0.15	2.8	2.2	27.3	72.1	55.8
KPME: 3 mm day^{-1}	0.13	0.23	0.51	0.26	0.20	2.6	2.6	16.0	54.5	60.2
KPME: 6 mm day^{-1}	0.15	0.22	0.42	0.25	0.20	2.3	1.9	17.9	58.9	44.6
WAS: 1.5 mm day^{-1}	0.19	0.31	0.72	0.24	0.55	3.0	1.2	33.6	190.5	79.2
WAS: 3 mm day^{-1}	0.21	0.27	0.64	0.29	0.33	2.9	1.8	19.8	235.2	70.3
WAS: 6 mm day^{-1}	0.20	0.25	0.53	0.29	0.29	3.0	2.1	12.1	174.6	69.6
[Y] $HSD_{0.05}$										
Irrigation Source (IS)	0.02	0.04	0.06	0.03	0.04	0.2	n/a	3.5	29.5	12.1
Application Rate (R)	0.02	0.03	0.05	0.03	ns	0.2	n/a	2.7	ns	9.5
Cut (C)	0.01	0.02	0.03	0.01	ns	0.1	n/a	1.6	12.3	ns
IS x R	ns	0.08	ns	ns	0.10	0.5	n/a	ns	66.3	27.2
IS x C	0.03	ns	0.09	0.05	ns	0.3	n/a	5.0	38.7	16.2
R x C	ns	ns	ns	0.04	0.06	ns	n/a	ns	31.4	13.1
IS x R x C	ns	ns	0.18	0.09	0.14	0.6	n/a	10.2	79.5	33.3

[Z] TWP – Tap water (control); ME – Municipal Effluent; KPME – Kraft pulp mill effluent; WAS – Waste Activated Sludge

[Y] HSD – Tukey's Honest Significant Difference Test (P=0.05)

ns = not significant; n/a = statistical analyses not conducted

Table 3.5. Mean soil analyses (n=4) for NO_3, PO_4, K, SO_4, B, Fe, Mn, and Zn for soils irrigated with control (TPW), municipal effluent (ME), Kraft pulp mill effluent (KPME) and waste activated sludge (WAS) planted with reed canarygrass (108 days of irrigation)

^{Z} Irrigation Source: Rate	NO_3	PO_4	K	SO_4	B	Fe	Mn	Zn
	mg kg^{-1}							
TPW: 1.5 mm day^{-1}	101.6	18.2	113.6	49.9	0.7	118.8	2.5	2.4
TPW: 3 mm day^{-1}	63.3	16.7	103.4	55.1	0.7	122.0	1.6	2.0
TPW: 6 mm day^{-1}	15.2	13.5	87.3	59.9	0.7	121.0	1.0	2.1
ME: 1.5 mm day^{-1}	132.8	19.4	108.3	81.0	1.0	117.6	2.5	2.3
ME: 3 mm day^{-1}	53.1	19.1	110.6	44.3	1.1	133.3	2.3	2.5
ME: 6 mm day^{-1}	27.9	18.0	91.0	60.0	1.1	128.5	1.1	2.2
KPME: 1.5 mm day^{-1}	92.7	18.9	115.1	336.9	0.8	113.0	3.0	1.5
KPME: 3 mm day^{-1}	48.9	16.4	109.3	465.1	0.8	112.4	1.5	1.3
KPME: 6 mm day^{-1}	10.6	14.2	105.1	593.9	0.8	116.8	1.0	1.9
WAS: 1.5 mm day^{-1}	142.3	50.3	176.8	293.9	1.0	105.6	53.0	3.4
WAS: 3 mm day^{-1}	125.3	76.2	165.6	459.3	1.1	102.0	59.6	5.6
WAS: 6 mm day^{-1}	109.8	88.2	154.1	767.0	1.3	90.9	68.5	6.4
^{Y} Application Rate								
1.5 mm day^{-1}	117.3	26.7	128.4	190.4	0.9	113.8	15.3	2.4
3 mm day^{-1}	72.6	32.1	122.2	255.9	0.9	117.4	16.3	2.8
6 mm day^{-1}	40.9	33.5	109.4	370.2	1.0	114.3	17.9	3.1
^{Y} Irrigation Source								
TPW	60.0	16.2	101.4	55.0	0.7	120.6	1.7	2.1
ME	71.3	18.8	103.3	61.8	1.1	126.5	2.0	2.3
KPME	50.7	16.5	109.8	465.3	0.8	114.0	1.8	1.6
WAS	125.8	71.5	165.5	506.7	1.1	99.5	60.4	5.2
^{X} $HSD_{0.05}$								
Irrigation Source (IS)	22.2	21.9	28.8	87.4	0.2	6.5	19.6	1.2
Application Rate (R)	17.5	ns	ns	68.9	ns	ns	ns	ns
IS x R	49.1	ns	ns	193.6	ns	14.5	ns	ns

[Z] TWP – Tap water (control); ME – Municipal Effluent; KPME – Kraft pulp mill effluent; WAS – Waste Activated Sludge

[Y] Averages for application rate (1.5, 3, 6 mm d^{-1}) and irrigation sources (TPW, ME, KPME, WAS) main factor effects

[X] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

ns = not significant

Table 3.6. Mean soil analyses (n=4) for NO_3, PO_4, K, SO_4, B, Fe, Mn, and Zn for soils irrigated with control (TPW), municipal effluent (ME), Kraft pulp mill effluent (KPME) and waste activated sludge (WAS) planted with hybrid poplar (86 days of irrigation)

^{Z} Irrigation Source: Rate	NO_3	PO_4	K	SO_4	B	Fe	Mn	Zn
	mg kg^{-1}							
TPW: 1.5 mm day^{-1}	166.0	18.6	96.4	243.3	0.7	104.5	2.1	1.5
TPW: 3 mm day^{-1}	166.1	14.8	91.1	133.8	0.7	100.2	1.9	1.4
TPW: 6 mm day^{-1}	70.5	15.2	85.9	37.9	0.6	103.8	1.4	1.5
ME: 1.5 mm day^{-1}	133.6	18.6	99.1	38.6	0.8	102.0	2.1	1.5
ME: 3 mm day^{-1}	188.9	18.0	97.2	41.9	0.9	105.3	1.7	1.7
ME: 6 mm day^{-1}	104.1	16.3	88.5	29.6	0.9	108.2	1.6	1.6
KPME: 1.5 mm day^{-1}	155.0	17.6	103.9	222.2	0.7	98.9	2.3	1.6
KPME: 3 mm day^{-1}	174.5	18.5	108.0	366.8	0.7	95.7	2.1	1.7
KPME: 6 mm day^{-1}	85.8	17.4	106.1	351.1	0.7	97.4	1.2	1.6
WAS: 1.5 mm day^{-1}	159.3	55.3	147.9	141.7	1.1	98.7	43.0	5.6
WAS: 3 mm day^{-1}	224.0	68.4	168.4	276.4	1.2	78.1	42.9	11.4
WAS: 6 mm day^{-1}	189.2	70.3	171.6	251.9	1.4	67.2	39.5	9.0
^{Y} Application Rate								
1.5 mm day^{-1}	153.5	27.5	111.8	161.4	0.8	101.0	12.4	2.6
3 mm day^{-1}	188.4	29.9	116.2	204.7	0.9	94.8	12.1	4.1
6 mm day^{-1}	112.4	29.8	113.0	167.6	0.9	94.2	10.9	3.4
^{Y} Irrigation Source								
TPW	134.2	16.2	91.1	138.3	0.6	102.8	1.8	1.5
ME	142.2	17.6	94.9	36.7	0.9	105.2	1.8	1.6
KPME	138.4	17.8	106.0	313.3	0.7	97.3	1.8	1.7
WAS	190.8	64.7	162.6	223.3	1.3	81.3	41.8	8.7
^{X} $HSD_{0.05}$								
Irrigation Source (IS)	ns	15.9	25.4	101.6	0.2	15.2	12.4	3.0
Application Rate (R)	51.2	ns	ns	ns	ns	ns	ns	ns
IS x R	ns	ns	ns	225.1	ns	ns	ns	ns

^{Z} TWP – Tap water (control); ME – Municipal Effluent; KPME – Kraft pulp mill effluent; WAS – Waste Activated Sludge

^{Y} Averages for application rate (1.5, 3, 6 mm d^{-1}) and irrigation sources (TPW, ME, KPME, WAS) main factor effects

^{X} HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

ns = not significant

Table 3.7. Generalized trends for the impact of TPW, ME, KPME, and WAS on extractable nutrients within plant tissue (N, P, K, S, Ca, Mg, Na, B, Fe, Mn, and Zn) and the soluble (Na^+, Ca^{2+}, Mg^{2+}, K^+, and SO_4^{2-}) and extractable nutrient (N, P, K, S, B, Fe, Mn, and Zn) levels in analyzed soil samples. Trends of soluble Na^+, Ca^{2+}, Mg^{2+}, K^+, and SO_4^{2-} were taken from Patterson et al. (2008). The use of (>) does not necessarily represent a significant increase or decrease

Extractable								
N	Soil	WAS	>	ME	=	TPW	=	KPME
	Plant	WAS	≥	ME	≥	KPME	≥	TPW
P	Soil	WAS	>	ME	=	KPME	=	TPW
	Plant	WAS	>	ME	=	KPME	=	TPW
K	Soil	WAS	≥	ME	=	KPME	=	TPW
	Plant	WAS	≥	KPME	≥	ME	=	TPW
SO_4-S	Soil	WAS	≥	KPME	>	ME	≥	TPW
	Plant	TPW	>	ME	>	WAS	≥	KPME
B	Soil	WAS	=	ME	>	KPME	=	TPW
	Plant	ME	=	KPME	=	TPW	=	WAS
Fe	Soil	TPW	=	ME	=	KPME	>	WAS
	Plant	ME	=	WAS	=	KPME	=	TPW
Mn	Soil	WAS	>	ME	=	TPW	=	KPME
	Plant	WAS	>	KPME	=	ME	=	TPW
Zn	Soil	WAS	>	ME	=	TPW	=	KPME
	Plant	WAS	≥	ME	=	KPME	=	TPW

Soluble								
Na^+	Soil	WAS	=	KPME	>	ME	>	TPW
	Plant	WAS	≥	KPME	≥	ME	=	TPW
Ca^{2+}	Soil	WAS	>	KPME	>	ME	≥	TPW
	Plant	WAS	≥	ME	=	TPW	≥	KPME
K^+	Soil	WAS	≥	KPME	>	ME	≥	TPW
	Plant	WAS	≥	KPME	≥	ME	=	TPW
Mg^{2+}	Soil	KPME	≥	WAS	>	ME	=	TPW
	Plant	TPW	≥	ME	≥	WAS	=	KPME
SO_4^{2-}	Soil	KPME	≥	WAS	>	TPW	=	ME
	Plant	TPW	>	ME	>	WAS	≥	KPME

4. *EFFECTS OF DILUTED KRAFT PULP MILL EFFLUENT ON HYBRID POPLAR AND SOIL CHEMICAL PROPERTIES*

Agricultural and forest systems can play unique roles in treating municipal and industrial effluents. Traditionally, municipal and industrial effluents have been discharged to surface water for disposal; however, as regulatory guidelines become more stringent, alternate treatments, and disposal methods must be sought. As urban and industrial developments, continue to expand competition for land and need for potable water increase. Where and how effectively these potable water sources are being used must be re-evaluated. Effluents could serve as a source of water and nutrients for crop production, thereby reducing the demand for potable water for irrigation water and fertilizer inputs. Over the last two decades, use of effluent irrigation has become a favorable disposal and beneficial use alternative in arid areas on forages, eucalyptus, willow, pine (Stewart and Flinn, 1984; Myers et al., 1996), and poplar (Carlson, 1992). Previous studies have identified potential opportunities for effluent irrigation projects using hybrid poplars (*Populus* sp.) that have high water and nutrient use and economic value for pulp or wood products production (Carlson, 1992; Howe and Wagner, 1996; Carlson and Berger, 1998). Numerous clonal varieties of poplar are available through breeding programs to select clones tolerant of varying soil, climatic, and hydrologic conditions (Bañuelos et al., 1999; Shannon et al., 1999).

Land application of effluents, either for beneficial use or for disposal needs to include consideration for dissolved salt content of the effluent. The resulting impacts on soil sodicity and salinity directly affect plant growth, nutrient uptake, and soil nutrient availability. Tolerances of selected crops to exchangeable sodium and salinity are shown in Table 8.1 and Table 8.2 (Appendix – A). Changes in soil chemical (e.g., dissolved salts) and physical properties (e.g., dispersion and reduced infiltration) can negatively influence cropping systems over the long term (Balks et al., 1998; Halliwell et al., 2001). Sustainable irrigation with saline effluents requires sufficiently high leaching fractions to prevent salt accumulation within the rooting zone. Letey (1993) suggested that over-irrigation with effluents with high sodium adsorption ratio (SAR), to achieve appropriate leaching fractions, may not be detrimental to soil physical properties if dissolved salt concentrations of the percolating water are also high. Letey also suggested that, in the field, rain, which has similar properties to distilled water, causes a dilution effect, enhancing the deleterious effects of high sodium (Na) concentrations in soils. Although effluents are inherently different in composition, they share the fact that their management poses unique environmental concerns (Sparling et al., 2001). Discharging these effluents into surface water courses can lead to accumulation of nitrogen or phosphorus and eutrophication; their use in irrigation projects can lead to soil accumulation of Na, chloride (Cl), and boron (B) leading to soil salinization and ultimately affecting plant growth and development. Thus, disposal of effluents requires specific management strategies and guidelines to maximize potential benefits while minimizing potential adverse environmental impacts (Myers et al., 1999; Alberta Environment 2000).

Table 9.1 and Table 9.2 (Appendix – B) show some of the guidelines and parameters which should be considered when considering effluents as an irrigation source. Use of effluents for irrigation must consider effluent SAR and electrical conductivity (EC) (Rengasamy et al. 1984;

Rengasamy and Olsson 1993) and resulting impacts on soil properties like, infiltration rate, when effluent constituents include dissolved salts and significant concentrations of sodium (Figure 4.1). Effluent chemical composition is important in determining degree of impact on soil as well, since calcium (Ca^{2+}) in the effluent combined with high concentrations of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) will likely precipitate in the soil, thereby removing Ca^{2+}, and increasing the deleterious effects of Na^+ on soil (Ayers and Westcot, 1994; Halliwell et al., 2001). Improper irrigation management can result in high soil solution and exchange complex Na^+ concentrations, (Balks et al., 1998; Halliwell et al., 2001; Sparling et al., 2001), increasing soil dispersion, reducing hydraulic conductivity and infiltration capacity (Magesan et al., 1999), and osmotic potentials (Shani and Dudley, 2001). Soils irrigated with high salinity waters remain structurally stable while those of high sodicity result in unstable soil structure due to Na-induced dispersion (Buckland et al., 2002; Tillman and Surapaneni, 2002).

In sub-humid to semi-arid environments, deficit supplemental irrigation strategies could be adopted for effluent irrigation. Then excess irrigation water or annual precipitation could be relied on to flush ions from the root zone. Supplementing crop-water requirements with effluent could allow for growing season precipitation to provide additional moisture for leaching requirements necessary to minimize salt accumulations within the rooting zone. A previous growth chamber study (Patterson et al., 2008) indicated growth of hybrid poplar was water limited in a study with application rates up to 6 mm day^{-1}; results indicated greater rates could potentially be utilized. Kraft pulp mill effluents (KPME) contain significant amounts of Na^+, sulphate (SO_4^{2-}), and Cl^-. Thus, increasing application rates will provide additional water. Decisions in this regard need to consider whether the increase is accomplished using effluents or better quality waters, as the use of effluent will also increase dissolved ions or nutrients added to the soil.

Saline-sodic effluents have specific management issues, which unless managed properly can lead to an unsustainable irrigation program. Effluent reuse through irrigation is a beneficial way of conserving water and provides one means of nutrient recycling. Reduced demands on potable sources of water are positive as is reduced nutrient loadings to surface and ground water sources. A better understanding is required of the relevant management strategies if effluent applications are to be managed to maximize utilization with minimal environmental impact, Patterson et al. (2008a 2008c) found the application of KPME increased ECe and SAR of soil, and biomass and nutrient uptake of irrigated crops (Patterson et al., 2008b). Diluting KPME with DW, or better quality waters could reduce the degree to which ECe, SAR, and soluble ions are increased while not adversely affecting crop growth. A growth chamber experiment conducted by Bauder and Brock (2001) found crop and amendment combinations significantly affected saline soil reclamation. The authors documented 15 irrigations with saline-sodic effluents (SAR_{adj} = 16.6; TDS 1647 mg L^{-1}) increased soil EC but did not adversely affect crop yields compared to irrigation with water with low SAR_{adj} (1.15) and low TDS (747 mg L^{-1}). Combining DW with effluents would dilute concentrations of ions in solution and should therefore reduce the degree to which ECe, SAR, and the respective ions are increased in the soil.

Irrigation with KPME effluents may lead to reduced productivity unless managed properly. The objectives of this growth chamber study were to determine the effects of high application rates of KPME effluent and the use of distilled water as a supplemental water source on elemental loadings resulting from effluent applications and the resulting impact on tree growth and soil chemical properties.

4.1 MATERIALS AND METHODS

4.1.1 Experimental Design and Treatments

The upper 20 cm of an Ap horizon of an Eluviated Dystrochrept (Eluviated Dystric Brunisol) soil as sampled from a field south of a pulp mill operated by Alberta-Pacific Forest Industries at N54°55 latitude and W112°52' longitude, approximately 200 km northeast of Edmonton, Alberta, Canada. This slightly acidic, sandy loam textured soil has low SAR and EC, but relatively high Ca^{2+} and SO_4^{2-} (Table 4.1). The area where the soils were collected consist of Brunisols, Orthic Gray Luvisols, and Humic Eluviated Gleysols (70% Tawatinaw series, O.GL; 20% Codesa Complex series, B and O.GL; and 10% Mapova series, H.EGL) based on the soil survey of the Tawatinaw map sheet (83-I) (Kjearsgaard, 1972). The site slopes west and northwest with 1 to 5% slope and undulating topography. The soils at the study site were classified as Eluviated Dystric Brunisols in the Agriculture Feasibility Study (Table 13.1 to Table 13.5, Appendix – F; Proudfoot 2000). The region receives an average 503 mm of precipitation annually (Environment Canada, 2005), with approximately 65% occurring during the May through September growing season.

PVC tubing, 15 cm inside diameter and 45 cm length, was filled with 30 cm of collected soil on top of 10 cm of sand placed at the bottom to allow drainage. Tube bottoms were covered with a 4-mm^2 fibreglass mesh to prevent topsoil and sand from falling out and to allow drainage. A 1500-mL Seamless™ flip top tube feeding bag was attached to the bottom of the tubings to collect leachate, which could be siphoned through a hose at the bottom of the feeding bag (Appendix – E: Figure 12.2). Hybrid poplar [*Populus deltoides x P. petrowskyana* L. (cv. Walker)] cuttings (15 cm) were planted in the center of each tube. Cuttings were watered with 200 mL of distilled water on days 1, 3, and 5 of the study prior to effluent treatment applications. Application rates were based on a previous growth chamber study by Patterson et al. (2008a and 2008b) and were 2 to 3 times greater than the seasonal moisture requirement of a young hybrid poplar plantation estimated at 375 mm which over 18-wks equates to approximately 3 mm d^{-1}) (Proudfoot 2000). Effluent and control treatments were applied over a 78 day period to provide the equivalent of 6 and 9 mm day^{-1}, resulting in 468 mm (8.3 L) and 702 mm (12.4 L) of effluent or water being applied, equivalent to 3 and 4.5 pore volumes, respectively, over the course of the study. Growth chamber conditions were a 16:8 hour (light:dark) photoperiod at an air temperature of 20:18 °C (day:night).

Kraft pulp mill effluent, distilled water (DW), and KPME/DW (50:50; v:v) combination (COMB) treatments were studied. The KPME was collected from the Kraft pulp mill on a weekly basis, transported to the growth chamber, and stored at room temperature (15°C). For each irrigation event, the combination treatments consisted of applying equivalent volumes of KPME and DW necessary apply equivalent 6 and 9 mm day^{-1}. Treatment rates were designated as DW-6, COMB-6, and KPME-6, and DW-9, COMB-9, and KPME-9, respectively.

4.1.2 *Effluent and Leachate Analyses*

Effluent and water samples were collected every four weeks (n=3) and analyzed for select chemical parameters (Table 4.1), according to standard methods for water and effluent analysis (APHA, 1998). Distilled water and effluents were analyzed by EnviroTest Laboratories (Calgary, Alberta). Effluents were collected on a weekly basis, transported to a growth chamber, stored at room temperature (15°C) and later analyzed by EnviroTest Laboratories (Edmonton, AB) (Table 4.1). Effluent and water samples were analyzed using methods outlined by the American Public Health Association (1998) for pH (Method 4500-H), electrical conductivity (ECw, Method 2510), alkalinity (Method 2320), total dissolved solids (TDS), total organic carbon (TOC, Method 5310B) and total Kjeldahl nitrogen (TKN, Method 4500N-C). Method 3120B was used and an inductively coupled plasma – optical emission spectrophotometer (ICP-OES) used to quantify various ions in solution (i.e., sulphate, calcium, potassium, magnesium and sodium). Chloride was determined colorimetrically (Method 4500; APHA 1998).

Leachate was collected throughout the study and frozen until the end of the study at which time samples were composited for each treatment to obtain enough sample for analyses. Analyses conducted were the same as those carried out for KPME and DW, according to the methods outlined by the APHA (1998). Sufficient leachate was collected from the 9 mm d^{-1} treatments but not from all 6 mm d^{-1} treatments. Analyses therefore were restricted to those for the 9 mm d^{-1} rate.

4.1.3 *Plant Growth Measurements*

Height and root collar diameter (RCD) for the hybrid poplar were measured weekly and used as indicators of plant growth. Height measurements were made on the main stem from the soil surface to the tip of the main bud. A small caliper was used to measure root collar diameter 2 cm above the base where the stem emerged from the cutting.

At the completion of the study, trees were harvested and total above ground biomass determined. Stems with leaves removed were cut into sections, weighed to determine fresh weight, then dried at 60°C for 72 hours to determine dry biomass. Total leaf area was determined on all leaves collected by passing each leaf through a leaf area meter (LiCor Model 3100). The top two leaves were used to determine dry biomass for subsequent tissue analyses. Leaves were then dried at 60°C for 72 hours to determine total dry biomass. Leaf area, total fresh weight (i.e., stems + leaves; TFW), and total dry biomass (i.e., stems + leaves) of these leaves were determined separately but later included in total measurements.

4.1.4 *Tissue Analyses*

Stem tissue and the top two leaves of the hybrid poplar collected at the end of the study were analyzed for S, Cl, K, Ca, Mg, and Na. For each tree, the two dry leaves and whole stem were ground to a fine powder using a small coffee grinder and analyzed using methods APHA 4110B for Cl and APHA 3120B for the remaining elements according to methods outlined for nutrients in animal feed (Kalbasi and Tabatabai 1985; AOAC 1990). Uptake of S, Cl, K, Ca, Mg, and Na was calculated by multiplying dry biomass by tissue concentration of each element from leaf and stem results; values for leaves and stems were added to determine above ground plant uptake.

Uptakes for all treatments were referenced to that of the DW control treatment.

4.1.5 Soil Analyses

Samples (n=3) following initial collection were analyzed prior to the beginning of the study to establish baseline properties (Table 4.1). Post-treatment samples randomly selected from four of the eight replicates were collected at depth increments of 0 to 10 and 10 to 20 cm for analyses; the underlying soil was not analyzed. All soil samples were dried and ground to pass through a 2-mm sieve. A pressure plate apparatus was used for determining water holding capacity of disturbed samples according to Topp et al. (1993); the hydrometer method was used for soil texture analyses (Sheldrick and Wang, 1993).

Saturated paste extracts were analyzed for pH, ECe, (Hendershot et al. 1993), SAR, soluble K^+, Na^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-} (Janzen 1993) and soluble Cl^- (AHPA 1998). Deionized water was added to saturate the soil. After sitting overnight, an extract was obtained by vacuum filtration and individual cations (Ca^{2+}, K^+, Mg^{2+}, and Na^+) and anions (SO_4^-) were determined with an Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) (Janzen 1993) and ECe and pH measured using their respective meters. Soluble Cl^- was analyzed using the mercuric thiocyanate colorimetric method and quantified using a Technicon Autoanalyzer (APHA 1998).

4.1.6 Statistical Analyses

The completely randomized design had three effluent treatments and two rates, replicated eight times. A two-way analysis of variance (ANOVA) was conducted on soil analytical data using irrigation source [DW, COMB, KPME] and rate (6 and 9 mm day^{-1}) as main factors using SAS PROC MIXED (SAS Institute 2001). Statistical analyses were not conducted on leachate samples as only 2 samples from DW-9 produced enough leachate for analysis. Analyses of Variance (ANOVA) were conducted on hybrid poplar biomass, tissue, and soil chemical data using SAS. Two-way ANOVAs were conducted separately on soil chemical data for each depth increment. A significance level of 0.05 was selected and differences among means determined only if the F value of the ANOVA was significant. Main effects were not compared if interactions were significant. Statistical differences among means were determined using Tukey's HSD test and all statements of significance made at P=0.05; $HSD_{0.05}$ was calculated only when main factors [irrigation source (IS) and rate (R)] or respective interactions (irrigation source-by-rate (ISxR) were determined significant by their respective F value.

4.2 RESULTS AND DISCUSSION

4.2.1 Irrigation Sources

KPME is a slightly alkaline effluent with moderate concentrations of Ca^{2+}, potassium (K^+), and EC but high concentrations of Na^+, Cl^-, high total dissolved solids (TDS), bicarbonate (HCO_3^-), and SO_4^{2-}. Thus, increased soil pH, ECe, SAR and SO_4^{2-}, Cl^-, Ca^{2+}, K^+, and Na^+ concentrations could be expected under irrigation with KPME. Anticipated increases in soil chemical properties are likely to affect the uptake of these elements by the crop. The SAR were adjusted (SAR_{adj})

according to Ayers and Westcot (1994) to account for high HCO_3 concentrations. This was done to account for the greater HCO_3^- concentrations in the effluent that when applied as an irrigation source causes Ca^{2+} and Mg^{2+} to precipitate forming insoluble $CaCO_3$ or $MgCO_3$. As a result, the effect on soils can be underestimated without taking into account the additional HCO_3^-. SAR_{adj} (14.7) and EC (2.3 dS m^{-1}) were comparable to those of KPME used in the previous study where SAR_{adj} was 14.5 and EC was 2.5 dS m^{-1} (Patterson et al., 2008a and 2008b). Both values are higher than long-term averages of 10.5 SAR_{adj} and 2.0 dS m^{-1} ECw for KPME produced at the mill, which supplied the effluent. According to FAO water quality standards (Ayers and Westcot, 1994), KPME used in this study is 'Potentially Hazardous' (close to the safe line) for irrigation. The long-term average KPME falls along the border of 'Potentially Hazardous' and 'Safe' (Figure 4.1). According to the classification scheme of Steppuhn and Curtin (1993), effluent SAR was slightly too high for routine irrigation and would require additional soil monitoring.

Dissolved Na+, K+, Ca2+, Mg2+, Cl-, SO42-, HCO3-, and CO32- results were plotted in Piper diagrams for long-term KPME data and for the three irrigation sources (DW, COMB, and KPME) used (Figure 10.1, Figure 10.2, and Figure 10.4; Appendix – C). Data over the long-term for KPME show, the dominant cation being Na+ (~95%) in solution, while SO42- (50-60%), HCO3- + CO32- (25-35%) are the dominant anions followed by Cl- (15-20%) in solution (Figure 10.1). The major cations in solution for the control (DW) were dominated by Na+ + K+ (75%), Ca2+ (20%) followed by Mg2+ (5%) in solution, while anions were dominated by HCO3- + CO32- (65%), Cl- (25%), and SO42- (10%), in solution (Figure 10.2). The parameters for the KPME used in the experiment were comparable to the long-term values (Figure 10.4).

4.2.2 Plant Growth

At study completion, hybrid poplar height was greater in COMB and distilled water treatments relative to KPME at both rates (Figure 4.2). The 9 mm day^{-1} treatment significantly increased tree height. COMB-6 height was significantly greater than that for DW-6 or KPME-6. Average COMB-9 and DW-9 heights were not significantly different from each other, but they were significantly greater than that measured for KPME-9. Biomass increased when the rate was increased from 6 mm d^{-1} to 9 mm d^{-1} with the exception of KPME (Figure 4.3).

Leaf area and biomass of COMB and DW treatments were significantly greater than those of KPME at both rates. However, biomass (Figure 4.3) decreased significantly between COMB and KPME. Biomass from COMB across rates was slightly less (6.7%) than that for DW; KPME had biomass 44.3% lower than DW. In a greenhouse experiment, Howe and Wagner (1996) found biomass of cottonwoods increased with added sludge or manure; effluent pH increased, but not irrigation water salinity. Leaf area increased only with increasing rate for COMB (Table 4.2). Leaf drop from lower portions of the tree towards the end of the experiment was greater in KPME than in DW and COMB treatments (visually determined) and was supported by the significant decrease in leaf dry biomass (data not shown). Leaf drop was greatest for KPME-9, potentially suggesting the trees were attempting to compensate for reduced osmotic potentials developing within the soil due to effluent applications.

4.2.3 Tissue Analyses

Effluent type significantly affected leaf (Table 4.2) concentrations of S and Mg and stem (Table 4.3) concentrations of total S, Cl, Ca, Mg, and Na. Leaf tissue S (Table 4.2) increased non-linearly as KPME increased, comparable to the previous study by Patterson et al. (2008). Leaf tissue S (Table 4.2) from COMB and KPME was significantly greater than that from DW, but not significantly different from each other. The same trend occurred with stem tissue (Table 4.3). Uptake of S within all four treatments containing KPME was higher than that for DW, by 15 to 201%. The increased SO_4^{2-} uptake during each irrigation was expected and is related to the high concentration of SO_4^{2-} added through KPME for COMB and KPME. However, uptake of SO_4^{2-} by stem tissue in the COMB-6 treatment accounted for only 0.10% of SO_4^{2-} applied and increased slightly to 0.21% for KPME-6. At 9 mm d^{-1} only 0.12% (COMB) and 0.15% (KPME) of applied SO_4 was accounted for. Stem uptake is important, as it would be considered removal from the system once trees were harvested. Elemental removal by leaf tissue would be temporary, as nutrients removed would return to the system upon decomposition.

No significant differences were measured for Cl in leaf tissue (Table 4.2). Chloride in stem tissue was significantly greater in KPME than in COMB and DW, which were not significantly different (Table 4.3). Compared to DW-6, chloride uptake under COMB-6 increased 19% but decreased 38% when irrigated with KPME-6. Of the total Cl applied through COMB and KPME, stem uptake accounted for 0.7 to 1.2% and 4.1 to 28.1% of applied Cl, respectively.

Potassium plays an important role in osmotic regulation of water within the plant (Marschner, 2002). Neither leaf (Table 4.2) nor stem (Figure 4.3) tissue concentrations of K were significantly affected by any main factor or main factor interactions. Uptake of K in COMB-6 increased 18% while uptake within KPME-6 decreased 33% relative to DW, due to effluents.

Leaf tissue Na concentration was not significantly affected by either rate or irrigation source (Table 4.2). Stem Na (Table 4.3) concentration was significantly greater in COMB and KPME relative to DW. No significant difference was measured between COMB-6 and KPME-6. Of the total Na applied by COMB-6 only 0.064% was accounted for in stem and 0.04% in leaf tissue. These decreased to 0.03% and <0.01%, respectively, in KPME-6, comparable to Howe and Wagner (1996) who observed <0.002% of total Na input was taken up by cottonwood. This could be due to reduced water uptake under KPME, and as a result reduced Na uptake by poplar in response to increasing soil salinity caused by the KPME applications.

There was no significant effluent effect on leaf tissue concentration of Ca but a significant effect on Mg concentrations (Table 4.2). Concentration of Mg within leaf tissue of COMB was significantly lower than that of DW or KPME. Trends in concentrations of K and Mg in leaf tissue at 6 mm day^{-1} rate were opposite. The competitive interactions between K, Ca, and Mg in plant uptake may have played a role in the reduction of Mg uptake in this study since plant uptake of Ca or K can depress Mg uptake (Marschner, 2002). According to Marschner (2002) mineral nutrients, such as K^+, Ca^{2+}, and Mg^{2+} which are taken up as cations at cell wall exchange sites, the binding strength at these sites is smaller for Mg^{2+} because of the degree of hydration compared to K^+ or Ca^{2+}. As a result, K^+ or Ca^{2+} compete and depress the rate of Mg^{2+} uptake by the plant. Calcium helps strengthen cell walls and plays an important role as a secondary messenger for the growth and development of the plant. Potassium is important for photosynthesis and acts in the osmoregulation and water movement within the plant. Poplar tissue concentration of K, Ca, and Mg and total leaf dry biomass were greater in DW compared to COMB and KPME (data not shown). No significant difference in Mg leaf tissue concentration was measured between KPME and DW. In DW-9, more Ca and Mg was taken up than in COMB-9 or KPME-9. Stem tissue (Table 4.3) concentration of Ca and Mg was significantly greater in COMB-9 and KPME-9 relative to DW-9; significant differences were measured between DW, COMB, and KPME. Higher tissue concentrations of Ca and Mg were measured in COMB and KPME relative to DW (Figure 4.3). Compared to DW-6, irrigation with COMB-6 resulted in increases in uptake of 41% for Ca and 4% for Mg. Net decreases in KPME-6 relative to DW-6 were measured for Ca (-11%) and for Mg (-30%). Total plant uptake (i.e., stem uptake + leaf uptake) of Ca accounted for 100% of Ca applied by COMB-6, but only 36% of Ca applied by KPME-6. This decreased to 85% for COMB-9 and 28% for KPME-9. A similar observation was made for Mg with removals of 112% (COMB-6), 38% (KPME-6), 82% (COMB-9), and 29% (COMB-9), respectively.

4.2.4 Soil Chemistry

Soil pH in 0 to 10 cm ($HSD_{0.05}$ = 0.3) and 10 to 20 cm ($HSD_{0.05}$ = 0.2) depth increments showed significant irrigation source-by-rate interactions. In the 0 to 10 cm depth increment, soil pH, of the saturated paste extracts, were 6.2, 7.1, and 7.3 in DW-6, COMB-6, and KPME-6, respectively. At 9 mm d^{-1}, soil pH was 6.5, 6.8, and 7.2, respectively and was only elevated in COMB-9 and KPME-9 in both depth increments. In the 10 to 20 cm depth increment, soil pH for DW-6, COMB-6, KPME-6, and DW-9 was 6.2, significantly lower ($HSD_{0.05}$ = 0.2) than pH 6.7 and 7.0 measured in COMB-9 and KPME-9, respectively. Increases in saturated paste extract pH of soils irrigated with KPME were comparable to those found by Mancino and Pepper (1992). Irrigation with KPME likely elevated soil pH relative to DW, due to the greater Na^+ (Hayes et al. 1990) and HCO_3^- concentrations in KPME relative to DW. Mancino and Pepper (1992) suggested increases in soil pH could be attributed to the higher concentration of HCO_3^- in effluent, relative to potable water.

The ECe of irrigated soils analyzed from the 0 to 10 cm depth increment increased with increasing application rate, except for the DW treatment (Table 4.4), but the overall increase was less than that measured in the previous growth chamber study at the 6 mm d^{-1} irrigation rate (Patterson et al. 2008a). SAR, in the saturated paste extract, at this depth increment followed a similar trend to ECe with increases comparable to those from the previous study. Differences in ECe and SAR between studies can be attributed to effluent chemistry as effluent in the previous study had 27% more dissolved HCO_3^-, 18% more SO_4^{2-}, 23% more Cl^- and Ca^{2+}, 43% more Mg^{2+}, and 14% more Na^+ than effluent used in this study. Thus, differences in soil solution EC and SAR are most likely due to greater concentrations of these elements applied during each irrigation even though application rates were the same (6 mm d^{-1}). ECe of soils irrigated with COMB was 45 and 64% that of soils irrigated with KPME. SAR, in saturated paste extracts, for COMB-6 and COMB-9 was 59 and 83% of that measured within the respective KPME. ECe was increased in soils at both application rates, however, at the 9 mm d^{-1} elevated ECe likely would not affect growth of plants with moderate to high salinity tolerance (Wentz 2001). Bauder and Brock (2001) found irrigation with high SAR (SAR_{adj}=16.6)-high TDS (1647 mg L^{-1}) water increased soil EC but did not reduce alfalfa, barley, or sorghum-sudangrass yields compared to low SAR (SAR_{adj}=1.15)-low TDS (747 mg L^{-1}) water. Kraft pulp mill effluents contain substantial amounts of dissolved Na^+ (380 mg kg^{-1}) and less than 100 mg kg^{-1}, each, for Ca^{2+}, K^+, and Mg^{2+} (Table 6.2). Only KPME significantly increased soil soluble K^+ and no significant difference was measured between DW and COMB. There were no significant differences among treatments for soluble K^+ in the 10 to 20 cm depth increment (Table 4.5).

In the 0 to 10 cm depth increment, soluble Na^+ of the saturated paste extracts in soils irrigated with KPME and COMB was significantly greater than that of DW (Table 4.4). Averaged across both rates, COMB soluble Na^+ was 44% of that measured in KPME and increased to 59% in the lower depth increment. Soluble Na^+ in soil plus Na^+ removed via plant uptake accounted for 19.4% of Na^+ applied by COMB-9, and 18.1% applied by KPME-9. This suggests Na^+ may have leached through the soil or become bound by exchange complexes. Soluble Na^+ in the saturated paste extracts was increased significantly in soils irrigated with COMB and KPME at both rates. The increase in soluble Na^+ for COMB-6 and KPME-6 resulted in soil solution SAR of 7.5 and 8, while soil solution SAR of COMB-9 and KPME-9 were 12.6 and 12.0, respectively.

In the 0 to 10 cm depth increment, ISxR interactions were significant for soluble Ca^{2+} (Table 4.4). Concentrations of soluble Ca^{2+}, in saturated paste extracts, were greatest in soils irrigated with KPME at 9 mm d^{-1}; significantly greater than those for the other five irrigation treatments. Application rate increases lowered Ca^{2+} concentration in the 10 to 20 cm depth increment (Table 4.5). Likely increased plant uptake and leaching contributed to the decreased Ca^{2+}, but more likely precipitation may have played a role. No significant differences for Ca^{2+}, of the saturated paste extracts, were measured between soils irrigated with KPME-6 and COMB-9, or among DW-6, COMB-6, and DW-9. In the 10 to 20 cm depth increment, significant differences were found among all treatments with greatest concentrations found within KPME-6. Irrigation source-by-rate interactions affected soluble Mg^{2+}, in saturated paste extracts, in the 0 to 10 cm depth increment (Table 4.4), but only irrigation source affected Mg^{2+}, in saturated paste extracts, in the lower depth increment (Table 4.5). The trend in soluble Mg due to effluent application was similar to that of soluble Ca^{2+}.

In the 0 to 10 cm depth increment, irrigation source-by-rate interactions were significant for soluble Cl^- and SO_4^{2-}, in saturated paste extracts (Table 4.4). Their concentrations were greatest with KPME-9, similar to that for Ca^{2+} and Mg^{2+}. Soluble Cl^- concentration, in saturated paste extracts, followed a trend similar to that of soluble Ca^{2+}. Concentration of soluble SO_4^{2-} was significantly greater in KPME compared to COMB and DW. Again, no significant differences occurred among COMB-6, DW-6, and DW-9. No significant difference was measured in SO_4^{2-} concentration between COMB-6 and COMB-9. In the lower depth increment, concentration of Cl^- and SO_4^{2-}, in saturated paste extracts, only showed significant IS effects (Table 4.5) with the following trend measured, in saturated paste extracts: KPME > COMB > DW. Chloride (Cl^-) (Haruvy 2004) and SO_4^{2-} (Fuller 2001) could be utilized as environmental tracers for where Kraft effluents are utilized for irrigation for monitoring solute and nutrient movement through the soil profile.

4.2.5 Leachate Analyses

Leachate from soils irrigated with DW had elevated pH compared to COMB and KPME; which could be attributed to their higher bicarbonate concentrations. Leachate ECs from COMB and KPME treatments were 8.9 and 10.4 times greater than for DW (Table 4.6). Leachate from COMB and KPME treatments had Cl^- concentrations 17.8 and 18.6 times greater, respectively, than those from DW, while SO_4^{2-} concentrations were 207.8 and 254.9 times greater than those in DW. These results are expected, as KPME is high in HCO_3^- and Cl^-. For most parameters of Table 6, increased values were already evidenced for COMB (50% KPME).

The soil remaining at the bottom of the columns and the leachate likely contained most of the K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} applied during the study based on uptake and soil analyses in the two depth increments. Of the soluble ions present during the study (i.e., initial soil + effluent loading) only soluble K^+ applied by COMB-9 was fully accounted for, while 81% of Na^+, 10% of Ca^{2+}, 4% of Mg^{2+}, 62% of Cl^-, and 72% of SO_4^{2-} remained unaccounted for. With KPME-9 54% of K^+, 82% of Na^+, 58% of Ca^{2+}, 47% of Mg^{2+}, 75% of Cl^-, and 75% of SO_4^{2-} remained unaccounted for. The unaccounted Na^+, Ca^{2+}, and Mg^{2+} may have precipitated out of solution due to high concentrations of HCO_3^- added by COMB or KPME, while Cl^- and SO_4^{2-} were contained in the leachate. Concentrations of Cl^- (134 mg L^{-1}) and SO_4^{2-} (614 mg L^{-1}) in KPME (Table 4.6) were approximately 15 and 38 times greater, respectively, than background Cl^- and SO_4^{2-} in the pre-treatment soil. The anionic nature of Cl^- and SO_4^{2-}, coupled with different molecular size and charge, and low background soil concentrations, allow these ions to be used as mobile tracers (Fuller, 2001). Over time the increase in Cl^- and SO_4^{2-} resulting from effluent irrigation could lead to increased salt loadings of surface and groundwater.

4.2.6 Synthesis and Management Implications

The KPME contains high concentrations of dissolved Na^+ (380 mg L^{-1}), SO_4^{2-} (614 mg L^{-1}) and Cl^- (134 mg L^{-1}) (Table 4.1). The significantly higher Na^+, SO_4^{2-}, and Cl^- in KPME-6 and KPME-9 in both depth increments (Table 4.4 and Table 4.5) were likely responsible for leaf drop. As concentrations of Na^+, SO_4^{2-}, and Cl^- increased in the saturated paste extracts, so did soil salinity. Osmotic potentials likely decreased in soil, stressing poplar for water uptake. As root zone salinity increases, osmotic potentials are reduced and water uptake slows; this could only be speculated in the current experiment as no measurements were made. As a result, less nutrient uptake occurred (Bañuelos et al. 1999; Shannon et al., 1999). Leaf abscission in *Populus* clones occurred by 6 weeks under conditions of 12 to 15 dS m^{-1} (Bañuelos et al. 1999), and Shannon et al. (1999) attributed defoliation to salinity and the degree at which the clone is able restrict Cl^- uptake. Trees will maintain water uptake by dropping lower and older leaves reducing transpirational water loss to maintain turgor and to avoid water stress (Volkmar et al., 1998); like the leaf drop observed in this study. The degree of the stress response could be due to the clone studied having lower tolerance to salinity than other clones. Shannon et al. (1999) suggested hybrid poplar clones in their study had a salt tolerance threshold of 5.53 (±0.67) dS m^{-1} with a 12% decrease in yield for each unit increase in salinity. ECs, of the saturated paste extracts, in this study (maximum 3.5 dS m^{-1}; Table 4) were lower than those found by Shannon et al. (1999)

and Bañuelos et al. (1999).

To reduce the use of potable water for irrigation, KPME effluent could be used instead, provided ratios of KPME to water are kept below 1. Facilities like pulp or paper mills have the capability to utilize high quality water (e.g., river water) to supplement or dilute effluents for irrigation programs. Secondary effluents, like WAS, can be used to supplement the nutrient content of these irrigation sources.

Amounts of pulp mill effluent applied in the current study are 2 to 3 times higher than the annual precipitation for the study area. However, the study identifies possible upper limits for the use of such effluents to provide supplemental water under the right management conditions. The region where the study soil was collected receives approximately 340 mm (~2.7 mm d^{-1}) of precipitation from May to mid September with potential evapotranspiration rates (PET) estimated as 3 to 5 mm day^{-1}. The average daily water deficit of 0.3 to 2.3 mm throughout the summer could be reduced through irrigation. Taking into account seasonal periods where PET is at its peak (e.g., 5 mm d^{-1}) and using KPME to provide a supplemental source, the application rate of KPME would be slightly lower than that of the COMB-6 treatment used for this experiment. Even at this application rate, the increase in soil solution EC and SAR would be within tolerable limits of many crops including some clones of hybrid poplar. However, this assumes there would be a daily deficit of 2.3 mm d^{-1} for the entire growing season, which is unlikely for this area. A more realistic scenario would be where this deficit may occur for only a few weeks during the season, although the short term daily deficit would likely exceed 2.3 mm d^{-1}.

Supplemental irrigation approaches could be utilized to allow for effluent irrigation in sub-arid areas. To accomplish this, further research is needed on irrigation timing with different effluent sources at rates closer to what would be measured under field conditions. Full system analyses should be conducted to reduce concentrations of Na^+, SO_4^{2-}, and Cl^- in solution. Management options, including system and end of pipe approaches, could be evaluated including reducing waste streams that contribute to higher salt and nutrient loadings in the system. Implementation of technologies for acidifying the effluent to reduce concentrations of CO_3^{2-} and HCO_3^- within the effluent could also be evaluated. Other alternatives to dealing with Na^+ related issues include land application and incorporation of other amendments. Application of byproducts such as elemental S, lime, gypsum, manure, or other Ca amendments into the soil, or irrigation source, would also influence the success of an effluent irrigation program (Bauder and Brock, 2001). More research on irrigation timing and amendment combinations would be needed to verify these management options.

4.3 CONCLUSIONS

Rate limitations were evident as increasing the application rate from 6 to 9 mm d^{-1} of either DW or diluted effluent (COMB) treatments resulted in increased height and dry biomass of hybrid poplar trees. Under COMB, the increase in biomass was comparable to DW, but exceeded that under KPME. Under COMB, increases in height exceeded KPME at both rates but only at the low rate was the height under COMB greater than that under DW. Increasing the application rate resulted in greater soluble Na^+, SO_4^{2-}, and Cl^-, in the saturated paste extracts that over time can lead to reduced productivity related to lower osmotic potentials and infiltration rates. Diluting with DW provided the same amount of water with half of the KPME which Na^+, SO_4^{2-}, and Cl^-. Annual precipitation or supplementing effluents with marginal quality irrigation water would likely provide the necessary leaching to minimize accumulation of harmful concentrations of soluble salts in the rooting zone. Preliminary results indicate KPME could be used as a supplemental source of irrigation water provided its use was less than 50% of the total water requirement to avoid large increases in soluble ions like Na^+, SO_4^{2-}, and Cl^- which are related to soil salinity and sodicity. At a 50% dilution at 6 mm d^{-1}, ECe and SAR would be within tolerable limits of many crops like barley, wheat, reed canary grass, northern wheat grass, wild rye, and some clones of hybrid poplar.

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4.5 LITERATURE CITED

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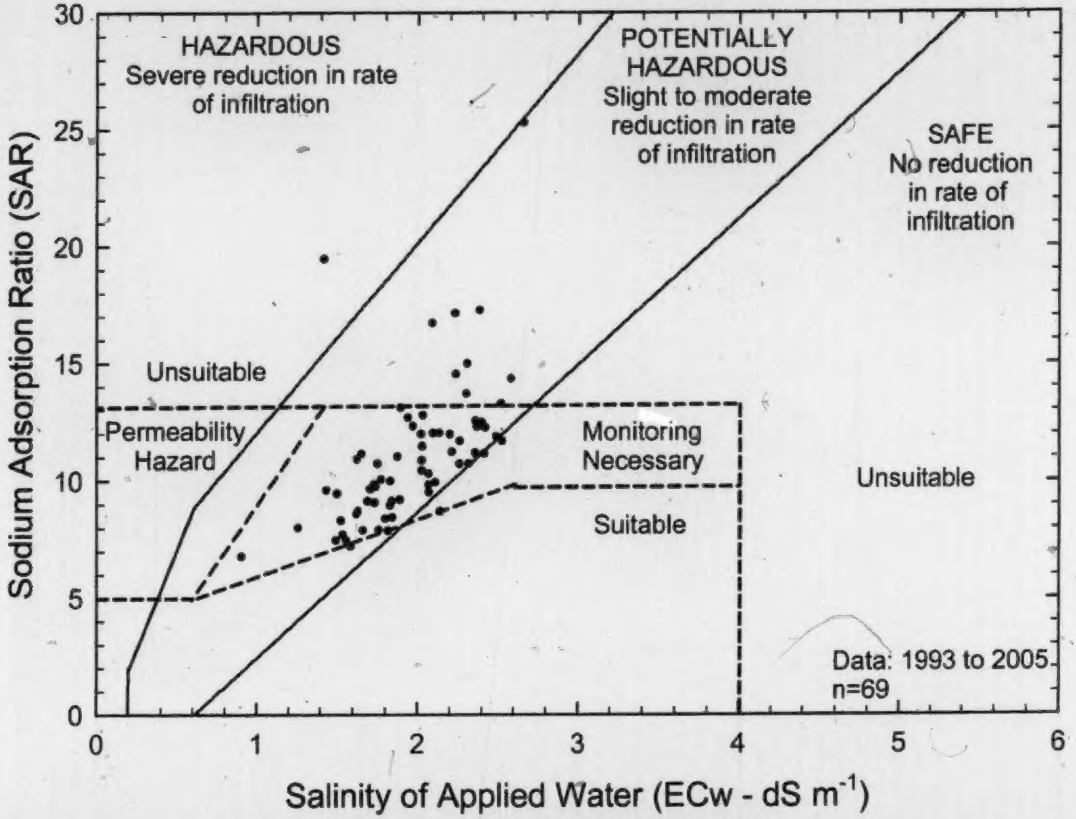

Figure 4.1. Impact of SAR_{adj} and EC_w on the relative rate of infiltration [modified from Ayers and Westcot (1994) and Steppuhn and Curtin (1993)]. Dashed lines outline areas for water quality, identified by Steppuhn and Curtin (1993) as (i) Unsuitable; (ii) Permeability Hazard; (iii) Monitoring Necessary; and (iv) Suitable (SAR<5 for fine textured soils). Points show the quality of the Kraft Pulp mill effluent produced by the pulp mill supplying the effluent used in this study.

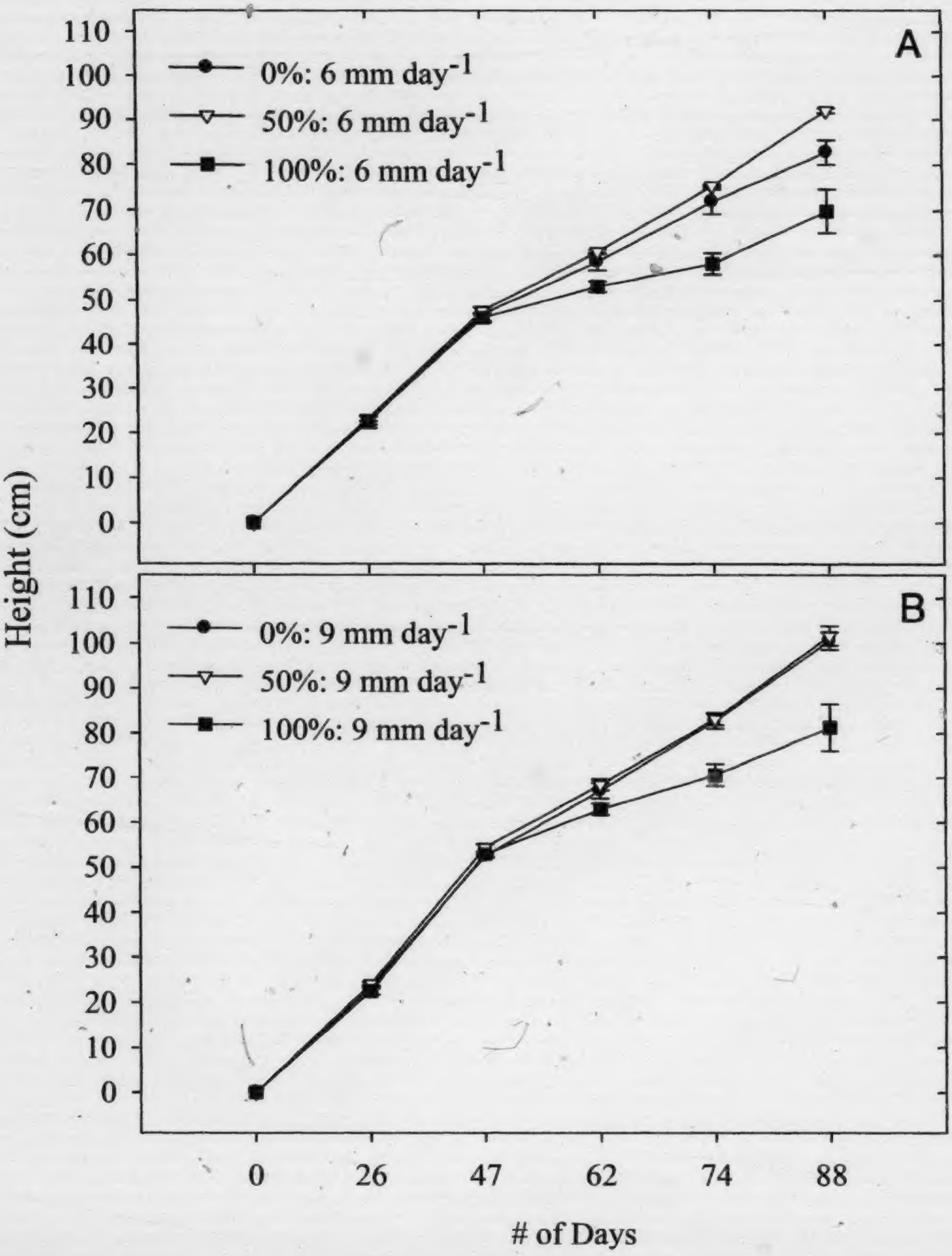

Figure 4.2. Average height of hybrid poplar with DW (0%), COMB (50%), and KPME (100%) effluents applied at rates of 6 (Figure left) and 9 mm d^{-1} (Figure right). The Tukey HSD$_{0.05}$ values are ±7.1 for effluent and ±5.9 for rate.

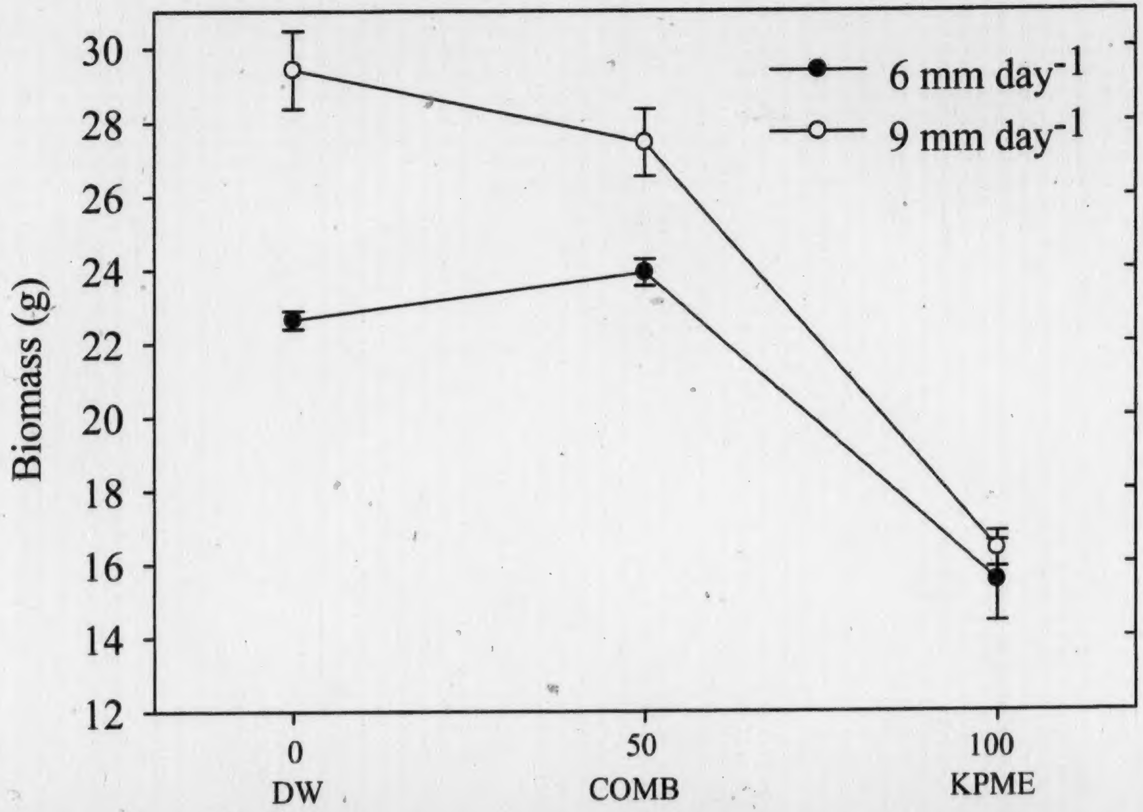

Figure 4.3. Average total dry biomass of hybrid poplar with DW (0%), COMB (50%), and KPME (100%) effluents applied at rates of 6 and 9 mm d^{-1}. Tukey's $HSD_{0.05}$ values are shown for the main factors irrigation source (IS), rate (R), and irrigation source-by-rate (ISxR) interaction. The Tukey $HSD_{0.05}$ values are ±1.6 for irrigation source, ±1.3 for rate, and ±2.3 for the Irrigation source-by-Rate interaction.

Table 4.1. Average (n=3) selected chemical and physical properties (± S.E.) of the study soil, distilled water (DW) and Kraft pulp mill effluent (KPME). Theoretical loadings (mg pot^{-1}) due to irrigation source applications at 6 mm d^{-1} for soils planted with hybrid poplar are also shown

				Loadings		
				8.3 L		
		[b] Distilled Water	Kraft Pulp Mill Effluent	Distilled Water	Combination	Kraft Pulp Mill Effluent
Characteristic	[a] Soil	(DW)	(KPME)	DW	COMB	KPME
Bulk Density (Mg m^{-3})	1.28					
[c] PAW (cm^3 cm^{-3})	24.4					
Texture						
Sand (g kg^{-1})	69.0					
Silt (g kg^{-1})	22.5					
Clay (g kg^{-1})	8.5					
pH	6.1	7.0	8.5			
[d] ECe; ECw (dS m^{-1})	0.56	0.01	2.26			
Saturation (%)	31.7					
[e] TDS (mg L^{-1})			1 493.3	17	6 206	12 395
HCO$_3$ (mg L^{-1})		5.0	380.7	42	1 600	3 160
CO$_3$ (mg L^{-1})		<5	7.7	na	32	64
[f] SAR	0.4	1.02	9.8			
[g] SAR$_{adj}$		0.19	14.7			
Ca (mg L^{-1})	62.2	<0.5	92.3	na	383	766
K (mg L^{-1})	12.5	<0.5	65.5	na	272	544
Mg (mg L^{-1})	7.8	<0.1	12.7	na	53	105
Na (mg L^{-1})	13.3	2.0	380.0	17	1 577	3 154
Cl (mg L^{-1})	9.3	<1	133.7	na	555	1 109
SO$_4$ (mg L^{-1})	16.3	<0.5	613.7	na	2 547	5 093

[a] mg kg^{-1} for soluble nutrients Ca^{2+}, K$^+$, Mg^{2+}, Na$^+$, Cl$^-$, and SO$_4^{2-}$ can be calculated using: mg kg^{-1} = % saturation/100 * mg L^{-1}

[b] DW – Distilled water control; COMB – DW/KPME Combination; KPME – Kraft Pulp Mill Effluent

[c] PAW – Plant Available Water: Pressure levels chosen for the loam textured Eluviated Dystric Brunisol soil for field capacity and wilting point were 10 kPa and 1500 kPa, respectively

[d] ECe - Electrical Conductivity of saturated paste extract; ECw – Electrical Conductivity of irrigation source

[e] TDS – Total Dissolved Solids

[f] SAR - Sodium Adsorption Ratio

[g] SAR$_{adj}$ - Adjusted Sodium Adsorption Ratio (Ayers and Westcot 1994)

na = not available as analyses results were below the detection limit

Table 4.2. Average leaf area (n=8) and leaf tissue concentrations (n=4) of S, Cl, K, Ca, and Mg (%) and Na (mg kg^{-1})

[a] Treatment Irrig. Source, Rate	Leaf Area	S	Cl	K	Ca	Mg	Na
	-- cm^2 --			%			mg kg^{-1}
DW, 6 mm day^{-1}	2 289	0.20	0.57	2.36	1.04	0.21	11.3
COMB, 6 mm day-1	2 294	0.58	0.64	2.61	1.42	0.20	23.0
KPME, 6 mm day^{-1}	1 594	0.68	0.51	2.35	1.33	0.21	1.0
DW, 9 mm day^{-1}	2 707	0.28	0.56	2.93	1.55	0.24	6.5
COMB, 9 mm day-1	2 656	0.54	0.52	2.78	1.42	0.20	21.5
KPME, 9 mm day^{-1}	1 551	0.61	0.48	1.77	1.54	0.23	31.5
[b] Irrig. Source (IS)							
DW	2 498	0.24	0.56	2.64	1.30	0.23	8.9
COMB	2 475	0.56	0.58	2.69	1.42	0.20	22.3
KPME	1 572	0.65	0.50	2.06	1.43	0.22	16.3
[b] Application Rate (R)							
6 mm day^{-1}	2 059	0.49	0.57	2.44	1.27	0.21	11.8
9 mm day^{-1}	2 305	0.48	0.52	2.49	1.50	0.22	19.8
[c] HSD$_{0.05}$							
Irrigation Source (IS)	211	0.09	ns	0.58	ns	0.02	ns
Application Rate (R)	143	ns	ns	ns	0.23	0.02	ns
IS x R	367	ns	ns	ns	ns	ns	ns

[a] DW – Distilled water control; COMB – DW/KPME Combination; KPME – Kraft Pulp Mill Effluent

[b] Averages for irrigation sources (DW, COMB, KPME) application rate (6 and 9 mm d^{-1}) main factor effects

[c] HSD – Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations

ns – not significant

Table 4.3. Average stem tissue concentrations (n=4) of S, Cl, K, Ca, and Mg (%) and Na (mg kg^{-1})

[a] Treatment Irrigation Source, Rate	S	Cl	K	Ca	Mg	Na mg kg^{-1}
	%					
DW, 6 mm day-1	0.04	0.57	0.97	0.78	0.09	15.5
COMB, 6 mm day-1	0.09	0.64	1.06	0.94	0.11	107.0
KPME, 6 mm day-1	0.12	0.51	1.01	1.09	0.13	122.3
DW, 9 mm day-1	0.04	0.56	0.89	0.76	0.08	9.3
COMB, 9 mm day-1	0.08	0.52	0.98	0.90	0.10	116.0
KPME, 9 mm day-1	0.13	0.48	1.02	1.15	0.14	147.8
[b] Irrig. Source (IS)						
DW	0.04	0.56	0.93	0.77	0.08	12.4
COMB	0.08	0.58	1.02	0.92	0.10	111.5
KPME	0.13	0.50	1.01	1.12	0.14	135.0
b Application Rate (R)						
6 mm day-1	0.08	0.57	1.01	0.94	0.11	81.6
9 mm day-1	0.08	0.52	0.96	0.94	0.11	91.0
c HSD0.05						
Irrigation Source (IS)	0.02	ns	0.09	0.12	0.02	39.8
Application Rate (R)	ns	ns	ns	ns	ns	ns
IS x R	ns	ns	ns	ns	ns	ns

[a] DW – Distilled water control; COMB – DW/KPME Combination; KPME – Kraft Pulp Mill Effluent

[b] Averages for irrigation sources (DW, COMB, KPME) application rate (6 and 9 mm d^{-1}) main factor effects

[c] HSD – Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations

ns – not significant

Table 4.4. Average (n=4) values for soil solution EC, SAR, and soluble K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} in the 0 to 10 cm depth increment

[a] Treatment Irrigation Source, Rate	[b] ECe dS m^{-1}	[c] SAR	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
			mg kg^{-1}					
DW, 6 mm day^{-1}	0.2	0.6	3.8	20	14	6	1.2	4
COMB, 6 mm day-1	1.2	7.5	12.5	42	311	13	3.7	93
KPME, 6 mm day^{-1}	2.6	12.6	21.8	100	941	28	6.0	261
DW, 9 mm day^{-1}	0.2	0.4	5.5	24	27	7	1.6	7
COMB, 9 mm day-1	1.7	8.0	14.8	77	571	22	4.3	167
KPME, 9 mm day^{-1}	3.5	12.0	38.3	174	1388	51	11.2	403
[d] Irrigation Source (IS)								
DW	1.4	7.7	13.6	59	441	17	4.0	130
COMB	0.2	0.5	4.6	22	20	7	1.4	6
KPME	3.0	12.3	30.0	137	1164	39	8.6	332
[d] Application Rate (R)								
6 mm day^{-1}	1.3	6.9	12.7	54	422	16	3.7	119
9 mm day^{-1}	1.8	6.8	19.5	92	662	27	5.7	192
[e] $HSD_{0.05}$								
Irrigation Source (IS)	0.4	0.8	8.6	30	196	9	2.6	59
Application Rate (R)	0.3	ns	5.8	20	132	6	1.7	40
IS x R	0.1	ns	ns	53	345	16	4.5	104

[a] DW – Distilled water control; COMB – DW/KPME Combination; KPME – Kraft Pulp Mill Effluent

[b] ECe – Electrical Conductivity of saturate paste extracts

[c] SAR – Sodium Adsorption Ratio

[d] Averages for irrigation sources (DW, COMB, KPME) application rate (6 and 9 mm d^{-1}) main factor effects

[c] HSD – Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations

ns – not significant

Table 4.5. Average (n=4) values for soil solution ECe, SAR, and soluble K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} in the 10-20 cm depth increment

[a] Treatment Irrigation Source, Rate	[b] ECe dS m^{-1}	[c] SAR	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
			----	----	mg kg^{-1}	----	----	----
DW, 6 mm day^{-1}	0.2	0.2	4.5	30	16	8	1.3	5
COMB, 6 mm day-1	1.8	7.9	9.3	87	638	25	2.7	185
KPME, 6 mm day^{-1}	3.0	9.6	15.3	173	1 233	52	4.6	373
DW, 9 mm day^{-1}	0.2	0.3	3.3	21	19	6	1.0	6
COMB, 9 mm day-1	1.9	8.5	11.3	85	685	25	3.4	205
KPME, 9 mm day^{-1}	2.9	11.4	18.5	113	1 154	32	5.3	328
[d] Irrigation Source (IS)								
DW	1.8	8.2	10.3	86	661	25	3.0	195
COMB	0.2	0.3	3.9	25	18	7	1.1	5
KPME	2.9	10.5	16.9	143	1 193	42	4.9	351
[d] Application Rate (R)								
6 mm day^{-1}	1.6	5.9	9.7	97	629	29	2.9	188
9 mm day^{-1}	1.7	6.7	11.0	73	619	21	3.2	180
[e] $HSD_{0.05}$								
Irrigation Source (IS)	0.3	1.0	6.3	31	161	9	1.8	47
Application Rate (R)	ns	0.7	ns	21	ns	6	ns	ns
IS x R	ns	ns	ns	ns	ns	16	ns	ns

[a] DW – Distilled water control; COMB – DW/KPME Combination; KPME – Kraft Pulp Mill Effluent
[b] ECe – Electrical Conductivity of saturate paste extracts
[c] SAR – Sodium Adsorption Ratio
[d] Averages for irrigation sources (DW, COMB, KPME) application rate (6 and 9 mm d^{-1}) main factor effects
[e] HSD – Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations
ns – not significant

Table 4.6. Average leachate properties (±SE; n=4) for the 9 mm d^{-1} treatment

[a] Treatment	Distilled Water (DW)	Combination (COMB)	Pulp Mill Effluent (KPME)
# of Samples	2	8	8
pH	8.2	7.8	7.9
[b] EC, dS m^{-1}	0.5	4.3 ± 0.4	4.9 ± 0.2
[c] TDS, g L^{-1}	0.3	3.8 ± 0.4	4.4 ± 0.2
Hardness, g L^{-1}	0.2	2.8 ± 0.3	2.9 ± 0.2
HCO_3, mg L^{-1}	225.5 ± 21.5	161.6 ± 15.7	179.0 ± 6.4
CO_3, mg L^{-1}	5.0	5.0	5.0
SO_4, mg L^{-1}	8.9 ± 1.9	1 838.8 ± 188.1	2 256.3 ± 102.3
Cl, mg L^{-1}	38.0 ± 4.0	677.5 ± 94.3	707.6 ± 54.5
Ca, mg L^{-1}	71.3 ± 2.7	923.4 ± 104.4	949.1 ± 71.8
K, mg L^{-1}	6.2 ± 0.5	18.4 ± 2.0	22.9 ± 1.6
Mg, mg L^{-1}	11.7 ± 0.8	130.2 ± 15.1	126.5 ± 10.0
Na, mg L^{-1}	14.5 ± 9.5	92.6 ± 5.4	295.6 ± 27.8
[d] SAR	0.4 ± 1.3	0.8 ± 0.1	2.4 ± 0.8
[e] SAR_{adj}	0.5 ± 0.3	1.4 ± 0.1	4.3 ± 0.5

[a] DW – Distilled water control; COMB – DW/KPME Combination; KPME – Kraft Pulp Mill Effluent
[b] EC – Electrical Conductivity
[c] TDS – Total Dissolved Solids
[d] SAR – Sodium Adsorption Ratio
[e] SAR_{adj} - Adjusted Sodium Adsorption Ratio (Ayers and Westcot 1994)
[na] not available as analyses results were below the detection limit

5. *GROWTH OF WINTER WHEAT IRRIGATED WITH DILUTED KRAFT PULP MILL EFFLUENT ON SOILS AMENDED WITH GYPSUM AND WOOD ASH*

Preservation of water quality continues to be a major environmental issue. Linked to these issues is the disposal of effluents into local or regional rivers and lakes. Industries and municipalities are consistently evaluating alternatives dealing with nutrient rich effluents while minimizing environmental concerns (Roygard et al. 2001; Sparling et al. 2001). With the exception of municipal effluent, most studies have focused on evaluating municipal and industrial biosolids, excluding the effluent component. Effluents can vary in composition from the final treated effluent (low in nutrients and solids, discharged into surface water sources) to secondary effluents consisting of slurries (containing higher nutrient concentrations and percentages of solids). Effluents in combination can allow one to serve as the water source (e.g., final effluent; KPME), while another as a supplemental source of nutrients (e.g., secondary effluents; WAS).

Nutrient and trace element concerns are often associated with the biosolid component of the waste stream, while soluble salts like K, Na, and Cl are issues in the liquid component due to their solubility. Table 9.1 and Table 9.2 (Appendix – B) show some of the guidelines and parameters which should be considered when considering effluents as an irrigation source. Over the last two decades, interest has grown in evaluating treatment of effluents as a viable option through land application or irrigation systems (Sparling et al. 2001). The management of effluent irrigation programs becomes central to the sustainability of such projects. Management strategies for effluent irrigation programs can include deficit or supplemental irrigation, crop selection, or soil amendments. Each can play an integral role, while tailored to suit the intended function of the project (i.e., crop production, water treatment, or water use).

Crop selection may alleviate concerns associated with effluent irrigation projects. Crops that can be used for non-food purposes (e.g., biofuels and biomass energy) have many cultivars and varieties adapted to a broad range of environmental conditions. Tolerances of selected crops to exchangeable sodium and salinity are shown in Table 8.1 and Table 8.2 (Appendix - A). Genetic diversity within a species can allow varied responses to different effluent compositions and environmental conditions (e.g., soil acidity, salinity, temperature). This provides unique opportunities to develop programs to minimize societal concerns and maximize economic returns. For example, *Populus* species consist of numerous clonal varieties available through various breeding programs, allowing selection for clones tolerant of various soil, climatic, and hydrological conditions (Bañuelos et al. 1999; Shannon et al. 1999). Shannon et al. (1999) suggested hybrid poplar (*Populus* sp.) and eucalyptus (*Eucalyptus* sp.) when grown under short rotation could be used to accumulate salts (i.e., Cl) and trace elements (i.e., B and Se) contained within effluents, in leaf and stem tissue. Crops like alfalfa (*Medicago sativa* L.), when irrigated with municipal effluent, produced greater yields than the best perennial grasses at lower application rates (i.e., <5 cm per week) while yields of reed canarygrass (RCG; *Phalaris arundinacea* L.) and tall fescue (*Festuca arundinacea* Schreb.) increased and were comparable to alfalfa at higher rates (i.e., 7.5 cm wk^{-1}) (Tesar and Knezek 1982). The authors attributed the yield increases to the rate of N applied and the ability of alfalfa to fix its own N at low rates. Species can also be important when considering effluent quality and application rates during irrigation seasons. For example, effluents with low N concentrations may be more suitable for alfalfa or clover (*Trifolium* sp.), while effluents with high N concentrations may be more suited for RCG or corn.

Recently there has been a focus on crop species such as alfalfa, reed canarygrass, corn, wheat, and canola for the production of cellulosic ethanol or biodiesel. Doing so could allow agencies faced with environmental concerns to grow crops under effluent irrigation that would not be directly consumed by humans or livestock. Projects could be developed where effluent irrigated crops are used strictly for the production of biofibres for creating panel board, biomass for the direct incineration for heat and electricity production, or production of biofuels, like ethanol or biodiesel, thus; removing issues associated with food crops.

During the growing season in sub-humid to semi-arid regions, evapotranspiration (ET) often exceed seasonal precipitation, resulting in less than optimal crop growth. Supplemental irrigation with effluent could provide the additional water required to achieve higher yields. Projects utilizing effluents could supplement crop-water requirements, thereby, enhancing growing season precipitation available to support crop growth, and if desired, provide additional moisture for leaching requirements necessary to reduce salt accumulations within the rooting zone. While not considered deficit irrigation (Fereres and Soriano 2007), this approach would provide full crop-water ET requirements, since under deficit irrigation, there is a greater chance of salts accumulating within and below the root zone, resulting in concerns over site sustainability, groundwater contamination, soil salinization, and increased sodicity (Balks et al. 1998; Bond 1998). Increased salts reduce osmotic potential (Shani and Dudley 2001), which negatively affects the productivity of agricultural and silvicultural crops. To alleviate this problem, excess irrigation water or precipitation can be used to flush salts from the root zone (Beltran 1999). Application of gypsum or lime products can supply additional Ca^{2+} or Mg^{2+}, which can reduce or displace Na^{+} concentrations present within the root zone of the soil (Howe and Wagner 1996). However, the effects of gypsum application may only be short-term depending on application rates. Calcium amendments (e.g., gypsum and lime) and organic amendments (e.g., crop residues, manure, or biosolids) can be used in combination with irrigation strategies and crop selection when using saline-sodic effluents (Sekhon and Bajwa 1993; Howe and Wagner 1996, 1999). Bauder and Brock (2001) found in a growth chamber experiment that crop and amendment combinations significantly affected saline soil reclamation. The authors documented 15 irrigations with saline-sodic effluents (SAR_{adj} = 16.6; TDS 1647 mg L^{-1}), which increased soil solution EC, but did not affect crop yields relative to those obtained with application of irrigation water with low SAR_{adj} (1.15) and low TDS (747 mg L^{-1}). However, the leaching fraction utilized in the study was insufficient to prevent salt accumulation.

If effluent applications are to be managed to maximize utilization with minimal environmental impact, a better understanding is required of the relevant management strategies. Patterson et al. (2008a; 2008b) found the application of KPME increased ECe and SAR of soil, and biomass and nutrient uptake of irrigated crops. Diluting KPME with DW reduced the degree to which ECe, SAR, and soluble ions were increased but biomass was comparable or greater than that measured in the DW irrigation treatment (Patterson et al. 2008c). Combining DW with effluents diluted concentrations of ions in solution and should therefore reduce the degree to which soil ECe, SAR, and the respective ions are increased in the soil. Calcium amendments like gypsum or wood ash should increase Ca^{2+} and Mg^{2+} in solution thus helping mitigate the degree to which SAR is increased in the soil. The objectives of this growth chamber study were to determine the effects of two calcium amendments in conjunction with effluent irrigation on: (1) the biomass of and nutrient uptake by winter wheat and (2) selected soil chemical parameters, specifically soluble Na^{+}, Ca^{2+}, Mg^{2+}, SO$_4^{2-}$, and Cl^{-}.

5.1 MATERIALS AND METHODS

5.1.1 Effluent Analyses

The Kraft pulp mill which supplied the KPME and WAS for the study is located at 54°55 latitude and 112°52' longitude, approximately 200 km northeast of Edmonton, Alberta, Canada. The pulp mill operates an activated sludge system as part of the effluent treatment process at the facility (Figure 11.1, Appendix – D). Activated sludge systems have a high level of effluent treatment composed of various stages of aeration, flocculation, and solids separation (Smook 1989). Activated sludge is circulated through the system continuously to supply a constant supply of nutrients and biological organisms necessary for treatment. The term waste activated sludge (WAS) refers to excess sludge removed from the system to remove excess solids and reduce chances of nutrient and biological imbalances in the process.

Effluent collection for the Kraft pulp mill effluent (KPME) occurred at the final sampling building, prior to effluent discharge to the Athabasca River. The waste activated sludge (WAS) was collected from the return screens near the screw presses used for dewatering WAS and removing the suspended solids. Effluents were collected on a weekly basis and transported to a growth chamber for application. Effluents were stored for a maximum of seven days at room temperature (15°C) for use in the study. Effluent (n=4) and water (n=4) samples were analyzed by EnviroTest Laboratories (now ALS Laboratories) during the study using methods outlined by the American Public Health Association (APHA 1998) for pH (Method 4500-H), electrical conductivity (ECw) (Method 2510), alkalinity (Method 2320) and Total Dissolved Solids (TDS) (Table 5.1). Method 3120B ICP-OES was used to quantify ions in solution [(e.g., sulphate (SO$_4^{2-}$), calcium (Ca^{2+}), potassium (K^{+}), magnesium (Mg^{2+}), and sodium (Na^{+})]. Chloride was determined by colorimetry (Method 4500; APHA 1998).

5.1.2 Soil and Amendment Analyses

The soil used in this growth chamber study was obtained from the top 20 cm of a coarse textured Eluviated Dystric Brunisol. The area where the soil was collected consists of Brunisols, Orthic Gray Luvisols, and Humic Eluviated Gleysols (70% Tawatinaw series, O.GL; 20% Codesa Complex series, B and O.GL; and 10% Mapova series, H.EGL) based on the soil survey of the Tawatinaw map sheet (83-I) (Kjearsgaard 1972). The soils at the study site were classified as Eluviated Dystric Brunisols in the Agriculture Feasibility Study (Table 13.1 to Table 13.5; Appendix – F, Proudfoot 2000). The site slopes west and northwest with 1 to 5% slope and undulating topography. Selected physical and chemical properties of the soil, wood ash, and gypsum are reported in Table 5.2.

Recycled wallboard gypsum was provided by Bio-Cycle Nutrient Solutions Ltd. (Red Deer, AB) and wood ash supplied by the pulp mill in this study. Wood ash is produced at this mill by a cogeneration system resulting from the incineration of hog fuel (waste wood, bark, etc.) to produce heat, steam, and electricity. Ground wood ash, gypsum, and soil (Table 5.2) (pre and post) samples were analyzed for available NO_3 (Maynard and Kalra 1993) and SO_4 (Combs et al. 1998) using a 0.01M $CaCl_2$ solution. Soil analyses were conducted on three randomly selected replicates at the end of the study while analyses was conducted on one wood ash sample and one gypsum sample. A shake extraction was used for NO_3 (Maynard and Kalra 1993) and SO_4-S (Combs et al. 1998) analysis using dilute $CaCl_2$ solution. Analyses were conducted using a Technicon Autoanalyzer (Technicon Instruments Corp., Tarrytown, NY) for NO_3, while SO_4-S was analyzed using ICP-OES. A Modified Kelowna extraction (NH_4OAc + NHF + HOAc) was used for PO_4 and K analyses; PO_4 was analyzed using a Technicon Autoanalyzer and K with a Flame Photometer. Extraction of P and K was conducted using the Modified Kelowna extraction (NH_4OAc + NHF + HOAc) (Qian et al. 1994). The P was analyzed using a Technicon Autoanalyzer and K measured using a Flame Photometer. Boron (B_{HWS}) was extracted in hot water (100°C for 5 minutes) and analyzed using ICP-OES (Gupta 1993).

Analyses were conducted on saturated paste extracts to determine soil pH, electrical conductivity (ECe) (Hendershot et al. 1993), SAR, soluble K^+, Na^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-} (Janzen 1993) and soluble Cl^- (APHA 1998). Deionized water was added to saturate the soil which was left overnight. An extract was then obtained by vacuum filtration and individual cations (Ca^{2+}, K^+, Mg^{2+}, and Na^+) and anions (SO_4^{2-}) in the extract were determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) (Janzen 1993) and ECe and pH were measured using a pH and EC meter, respectively. Soluble Cl^- was analyzed using the mercuric thiocyanate colorimetric method and quantified using Technicon Autoanalyzer (APHA 1998).

Gypsum and ash were applied at an equivalent of 15 t ha^{-1} dry weight basis (15.4 g; 0.77% w/w) separately to 2 kg of air dried soil and mixed thoroughly. This application rate represents the maximum rate at which wood ash can be applied annually under provincial regulations (Alberta Environment 2002). Standard 20-cm diameter pots were then filled with the topsoil/amendment mixture overlying 3 cm of sand, used to prevent soil loss from the bottom of the pots, while still allowing drainage to occur. Leachate was not collected in this study. One third of the pots contained no amendment, one third contained gypsum, and one third contained wood ash.

The rate used for all irrigation treatments was 6 mm d^{-1} in order to remain consistent with two previous studies conducted using pulp mill effluents (Patterson et al. 2008a; Patterson et al. 2008c). Previous studies included (see Sections 2.1, 3.1, and 4.1) applications of 6 mm d^{-1} of DW, KPME, WAS, or combination treatments of distilled water (DW) and KPME applied at a 50/50 (v/v) dilution. Distilled water, effluent, and water treatments used in this study consisted of a DW control, KPME, WAS, and three combination (COMB) treatments. Combination treatments consisted of two KPME/WAS combinations diluted with distilled water (COMB-25 and COMB-50) and one KPME/WAS combination without dilution (COMB-100) (Table 5.3). The numbers associated with COMB-X treatments represents the proportion the KPME/WAS combination relative to DW (v:v), for example, COMB-50 consisted of 50% DW and 50% KPME and WAS in equal portions. Distilled water, KPME, and WAS irrigation treatments were applied separately to each pot; the three combination treatments were mixed together according to the appropriate volumes by stirring, and then applied to each treatment, respectively.

Winter wheat was selected as the test crop since it allowed for the collection of multiple clippings during the course of the study for determination of biomass and nutrient uptake by the wheat. CDC Osprey, a hard red semi-dwarf winter wheat (winter wheat; *Triticum aestivum* L.) cultivar provided by Thrisk Farms Co. Ltd., was used in the study. The wheat had 98% germination and a 1000 kernel weight (KWT) of 30.2 g. Ten seeds were planted in each pot and watered initially with one application of 500 mL of distilled water. Pots were thinned back to seven plants once plants had fully emerged. Pots were watered every two days with water or effluent to provide the equivalent of 6 mm d^{-1} (188.5 mL d^{-1}; total volume applied 17.1 L). The study lasted 91 days and winter wheat was harvested at Day 36 (1st Cut), Day 57 (2nd Cut), and Day 91 (3rd Cut). After the first harvest, urea was dissolved in distilled water to provide the equivalent of 50 kg N ha^{-1} and applied to all pots in the study to minimize potential N deficiencies. The only additional N applied in the study was through effluent applications as none of the distilled water, gypsum, or wood ash contained enough N to maintain plant uptake requirements. Growth chamber conditions were a 16:8 h (light:dark) photoperiod at an air temperature of 15:12°C (day:night) for four weeks up to plant establishment, after which the temperature was increased to 20:15°C (day:night). During the growing period, pots were rotated weekly to compensate for potential variations in growth chamber conditions.

5.1.3 Plant Growth Measurements and Tissue Analyses

Biomass was measured on the winter wheat on Day 36, Day 57, and Day 91 by clipping samples 2 cm above the surface of the growth medium for all three harvests. Wheat samples were weighed after cutting and then dried at 60°C for 72 hours to determine above ground dry biomass for each pot, results for a given harvest were then averaged.

Once biomass was determined, tissue analysis was conducted on whole plants randomly selected from three of the five replicates. Plants used for the analyses were collected from the same pots from which soil samples were collected for analyses. Tissue samples were analyzed for N, P, K, S, Ca, Mg, Na, Cl, and B. Tissue samples were dried at 60°C for 72 hours and then ground to a fine powder using a small coffee grinder and analyzed using methods APHA 4110B for Cl, and APHA 3120B for the remaining elements according to the methods outlined for minerals in animal feed (Kalbasi and Tabatabai 1985; AOAC 1990). Plant uptake of K, S, Ca, Mg, Na, and Cl by winter wheat irrigated with DW, effluents, or combinations was only calculated for winter wheat grown on non-amended soils. For each cut uptake was determined by multiplying the biomass (g) of winter wheat by the corresponding tissue concentration (mg kg^{-1}) for each element from each cut, respectively. These were combined across cuts to determine total elemental uptake by above ground biomass. Uptake of each element was referenced to DW to determine relative uptake. Calculated uptake at 6 mm d^{-1} was then compared to the total effluent loading to determine percentage accounted for by plant uptake.

5.1.4 Statistical Analyses

The growth chamber study consisted of eighteen treatments composed of 6 irrigation treatments (Table 5.3) and three soil amendments based on gypsum, wood ash, and unamended soil, in a completely randomized design with five replicates.

Repeated measures analysis was conducted first with the main factor cut being the repeated measure. Cut was statistically significant so each cut was subsequently analyzed separately using a two-way analysis of variance (ANOVA) for all biomass and tissue analyses. Two-way analyses of variance tests were conducted using the effluent (e.g., KPME, WAS, DW, and COMB-25, COMB-50, and COMB-100) and amendment (i.e., non-amended, gypsum, and ash) as main factors using the statistical program SAS (SAS Institute Inc. 2001). The amount of tissue collected from the first harvest was insufficient to complete the full analyses; therefore, data from the first cut are not presented in this paper. Statistical differences among means were determined using Tukey's HSD test and all statements of significance made at $P=0.05$. Statistical differences among means for the main effects (i.e., irrigation source (IS) and amendment (A)) or respective interactions (i.e., ISxA) were only determined when F was significant ($P < 0.05$).

5.2 RESULTS AND DISCUSSIONS

5.2.1 Irrigation Sources

Sodium adsorption ratios were adjusted (SAR_{adj}) according to Ayers and Westcot(1994) to account for the high HCO_3^- concentrations in Kraft pulp mill effluents. Calcium and Mg^{2+} precipitate out of solution with CO_3^{2-} and HCO_3^-, thus increasing the deleterious effects of Na^+ (Ayers and Westcot1994; Halliwell et al. 2001). According to FAO water quality standards (Ayers and Westcot1994), the SAR_{adj} values for COMB-100, KPME, and WAS treatments of 9.1, 9.7, and 8.4 would be considered 'potentially hazardous' for use in irrigation. Mean Na^{2+} concentrations in the KPME (293 mg L^{-1}) and WAS (249 mg L^{-1}) in this study were lower than those of KPME (435 and 380 mg L^{-1}) and WAS (439 mg L^{-1}) used in previous studies, respectively (Patterson et al. 2008a; Patterson et al. 2008c), respectively. The SAR for KPME and WAS lie within the 'potential hazardous' and 'safe' categories requiring additional monitoring according to Steppuhn and Curtin (1993).

Data for long-term data for KPME and the four irrigation sources used in this experiment were plotted in Piper diagrams (Figure 10.1, Figure 10.2, Figure 10.4, and Figure 10.5; Appendix – C). Plotting long-term KPME data in the Piper Diagrams shows, the dominant cations being $Na^+ + K^+$ (~60-75%) in solution followed by Ca^{2+} (~30-35%), and Mg^{2+} at (~5%), while SO_4^{2-} (~45-65%) was the dominant anion in solution followed by $HCO_3^- + CO_3^{2-}$ ranged from (~20-35%), and Cl^- (15-25%) (Figure 10.1). The major cations in solution of the control (DW) was dominated by $Na^+ + K^+$ (~67%), Ca^{2+} (~25%) followed by Mg^{2+} (~8%) and in solution, while anions were dominated by $HCO_3^- + CO_3^{2-}$ (53%), Cl^- (~35%), and SO_4^{2-} (~12%) (Figure 10.2). Data collected from this growth chamber experiment for KPME (Figure 10.4) was comparable to the long-term values. For the waste activated sludge (WAS), dominant cations in solution were Na^+ (~56%), followed by Ca^{2+} (~36%) and Mg^{+2} (~8%), while anions were dominated by HCO_3^- + CO_3^{2-} (60%), Cl^- (22%), and SO_4^{2-} (18%) (Figure 10.5). For the combination treatments

(COMB), dominant cations in solution were $Na^+ + K^+$ (~60%), followed by Ca^{2+} (~32%) and Mg^{+2} (~8%) in solution, while anions were dominated by $HCO_3^- + CO_3^{2-}$ (~43%), SO_4^{2-} (~35%), and then Cl^- (~22%) (Figure 10.5).

5.2.2 *Winter Wheat Growth*

Biomass of winter wheat was significantly increased by COMB-25, COMB-50, COMB-100, WAS, and by wood ash. In all three cuts, with the exception of DW in the third (last) cut, wood ash significantly increased biomass compared to gypsum- and non-amended soil (Table 5.4). The increase in biomass resulting from the ash application is likely due to P, K, and S contained within the ash (Vance 1996; Patterson et al. 2004). There was no significant difference in biomass between non-amended and gypsum-amended soils. Irrigation source also significantly affected wheat biomass in each cut. WAS and COMB-100 consistently increased biomass; with a trend of WAS > COMB-100 > COMB-50 > COMB-25 > DW > KPME, likely due to the higher nutrient content (i.e., N and P) of WAS compared to DW or KPME (Patterson et al. 2008b). The WAS contains a similar nutrient content to combined biosolids produced by pulp and paper mills, which have been widely studied as soil amendments (Cabral et al. 1998; Jordan et al. 2002; N'Dayegamiye et al. 2002). These biosolids are a more concentrated form of waste activated sludge (WAS) which has undergone the dewatering process leaving a product with 65-70% solids and a final effluent, KPME. Biomass from KPME without a Ca amendment was not significantly different from that with DW.

Winter wheat grown under field conditions could allow more than one crop to be incorporated into an effluent irrigation program. Under a supplemental or cyclic irrigation program winter wheat can be seeded in the fall and established with good quality water (i.e., rainfall) with less stress on emerging seedlings than would occur if effluent was used (Naresh et al. 1993). As a result, effluent applications could possibly be applied earlier the following growing season.

5.2.3 *Nutrient Uptake*

Nitrogen concentration in winter wheat tissue was affected by amendment only in the second cut (Table 5.5) and both amendment and effluent in the last cut (Table 5.6). Averaged across effluent treatments, COMB-25, COMB-50, COMB-100, and WAS removed 26, 42, 86, and 206% more N than DW. Tissue N concentration from ash-amended soils was significantly lower than those from non-amended and gypsum-amended soils, likely due to a dilution effect caused by greater biomass on ash-amended soils. Nitrogen concentrations were also affected by effluent applications and were significantly lower in DW and KPME, compared to COMB-25, COMB-50, COMB-100, and WAS.

Phosphorus concentration in the second cut of winter wheat tissue (Table 5.5 and Table 5.6), averaged across amendments was significantly higher for the COMB-25, COMB-50, COMB-100, and WAS compared to KPME and DW irrigation treatments. For both cuts, tissue P was not significantly different between DW and KPME or among COMB-50, COMB-100, and WAS. Tissue P concentration from COMB-25 was significantly lower in the last cut compared to

COMB-50, COMB-100, and WAS but was higher than those from KPME and DW. In the last cut, tissue concentration of P was only significantly different between ash and gypsum-amended soils.

No significant differences were observed in tissue K measured between DW and KPME (Table 5.5 and Table 5.6). These two treatments tended to have the lowest K tissue concentrations, again most likely due to a dilution effect and related to the lower N concentrations measured within these same tissues since N and K influence the uptake of each other (Marschner 2002). Tissue of wheat grown in ash-amended soils, averaged across effluents, had the highest K concentration in both cuts. This is surprising considering the ash would have supplied additional K in both total and available forms for plant uptake (Patterson et al. 2004). Under irrigation with COMB-25, COMB-50, COMB-100, KPME and WAS, K uptake of wheat grown on unamended soils increased 61, 51, 122, 2, and 225% higher, respectively, compared to DW accounting for 16.8 to 82.4% of the K supplied by the effluents, based on corresponding biomass (Table 5.4) and tissue analyses (Table 5.5 and Table 5.6).

Mean concentrations of tissue S (Table 5.5 and Table 5.6) for gypsum and ash-amended soils differed when averaged across effluents in the second cut. No significant differences in tissue S concentrations were measured between control soils and those grown on either ash or gypsum-amended soils. Except for WAS, tissue concentration of S was higher in gypsum-amended soils compared to control and ash-amended soils. Wheat grown on ash-amended soils tended to have the lowest tissue S, compared to both control and gypsum-amended soils, which can be attributed to both a dilution effect, caused by increased biomass but also to the availability of the SO_4 contained in the gypsum versus that contained in the ash. This indicates the SO_4 applied by the gypsum application was more soluble and as a result more available for plant uptake than SO_4 in the ash. Wheat grown on unamended soils and irrigated with COMB-25, COMB-50, COMB-100, KPME, and WAS had uptakes of S of 119, 121, 223, 39, and 260% higher, respectively, compared to DW, but accounted for only 0.2 to 1.5% of the SO_4 applied by these effluents during the study.

Tissue Ca concentrations (Table 5.5 and Table 5.6) were significantly affected by main factor interactions. Mean concentrations of the Ca averaged across effluents tended to be lower in DW and KPME compared to COMBs and WAS. Tissue Ca content in winter wheat tissue was higher in plants grown on gypsum-amended soils than those grown on ash-amended soils. Again, similar to what occurred for soluble SO_4, Ca applied in gypsum was more soluble and more available than that applied in the ash. Relative to DW when irrigated with COMB-25, COMB-50, COMB-100, and WAS, uptake of Ca was 45, 25, 99, and 180% higher, respectively, but 34% lower when irrigated with KPME. Calcium solubility is also affected by pH and by HCO_3 added through the effluent applications (Mancino and Pepper 1992). Calcium uptake accounted for 0.6 to 4.1% of that applied; no trends were evident in the concentration of Mg or Na in wheat tissue from either the second or the last cut (Table 5.5 and Table 5.6).

Tissue Cl concentrations (Table 5.5 and Table 5.6) of wheat for the second and last cut were lowest under irrigation with DW or KPME. Chloride uptake ranged from 91 to 645% in the effluent treatments relative to that of the DW control, but only accounted for only 1.4 to 8.1% of that applied by the effluents. The accumulation of Cl within the root zone can increase salinity, reducing crop growth. Tissues grown on control soils also had the highest Cl concentration compared to gypsum- or ash-amended soil. Boron uptake was influenced by the irrigation source-by-amendment interaction in the second cut and both effluent and amendment in the third. Tissue B in winter wheat was higher with DW relative to the other effluents, although the increase was only significant between DW and COMB-100.

5.2.4 Available Nutrients

Nitrate levels in the soil irrigated with KPME were comparable to those irrigated with DW (Table 5.7). Plant available PO_4 (Table 5.7) was higher with applications of COMB-50, COMB-100, and WAS than that measured in soils irrigated with DW. At the end of the study, average P concentration in the soil was higher in ash-amended soils compared to the control. Plant available P at the end of the study was comparable for non-amended and gypsum-amended soils, except for soils irrigated with DW, which exhibited greater variability. Plant available K (Table 5.7) was affected by soil amendment, with higher concentrations measured on ash-amended soils. Concentration of K from ash-amended soils was significantly different from the control and gypsum-amended soils, likely due to the higher K content of the ash (Vance 1996; Patterson et al. 2004). No significant differences in K concentration were measured between control and gypsum-amended soils. Plant available SO_4 concentrations were affected by the irrigation source-by-amendment (ISxA) interactions. Additional applications of Mg, due to its competitiveness with K for plant uptake, may be required to prevent nutrient imbalances in both the soil and plant because of the K applied through the ash (Marschner 2002; Patterson et al. 2004). Magnesium uptake is strongly depressed by the presence of cations such as Ca^{2+} and K^+ (Marschner 2002). According to Marschner (2002) for mineral nutrients, such as K^+, Ca^{2+}, and Mg^{2+} that are taken up as cations, binding strength, at cell wall exchange sites, is smaller for Mg^{2+} because of the degree of hydration compared to K^+ or Ca^{2+}. As a result, K^+ or Ca^{2+} compete and depress the rate of Mg^{2+} uptake by the plant. Calcium helps strengthen cell walls and plays an important role as a secondary messenger for the growth and development of the plant, while Mg is important for chlorophyll development. Potassium is important for photosynthesis and acts in the osmoregulation and water movement within the plant.

Concentrations of SO_4 were higher in gypsum- or ash-amended soils relative to non-amended soils and further increased by applications of the various effluents. Soil and amendment analyses (Table 5.2) revealed available SO_4 concentrations in the gypsum-amended soils were greater than these in the ash-amended soils, but soluble SO_4 was 39 times lower in gypsum than in the ash. This could be attributed to the methods of analyses of the amendments used and not the actual relationship between solubility and availability. Since SO_4 was determined analytically by ICP-OES the results of the wood ash could be attributed to the organic fraction of S contained in the ash compared to the SO_4 found in the gypsum that would be inorganic. Analyses of gypsum and ash used in the study indicated SO_4 solubility was greater in the ash but availability was greater in the gypsum. However, concentration of SO_4 was greatest in gypsum-amended soils. No significant trends were measured in plant available B and none of the treatments resulted in soil concentrations which exceeded CCME criteria (CCME 2006), unlike previous studies (Patterson et al. 2008b).

5.2.5 Soil pH, ECe, SAR, and Soluble Salts

Saturated paste extract pH was influenced by Irrigation Source-by-Amendment interactions (Table 5.8) and increased as a result of COMB, KPME, and WAS; further increases in ash-amended soils were also measured, compared to control or gypsum-amended soils. The elevated pH in KPME and WAS irrigated soils could have been increased as a result of the higher HCO_3^- concentrations, and resulting precipitation of Ca^{2+} or Mg^{2+}, caused by the effluents relative to DW (Harivandi 1999) and by the oxides and carbonates within the ash (Lickacz 2002).

Electrical conductivities (ECe) measured at the end of the study were lower than provincial and federal criteria for problem soils and would still be considered non-saline (CCME 2006). Wheat is moderately tolerant of salinity but would begin to experience yield reductions at ECs >7-8 dS m^{-1} (Wentz 2001). None of the treatments used in this study came close to approaching these values in the soil. ECe (Table 5.8) was affected by ISxA interactions with ECe, increasing because of effluent applications. ECe was higher in gypsum-amended soils, as gypsum, a salt itself, dissociates into Ca^{2+} and SO_4^{2-}. Sodium adsorption ratio in the soil used in this study was affected by irrigation source-by-amendment interactions (Table 5.8); it increased in soils irrigated with COMBs, KPME, and WAS. Lower SAR, in the saturated paste extracts, were measured in gypsum-amended soils, but gypsum did not reduce SAR to the same degree in soils irrigated with WAS (i.e., 0.6 units) compared to those soils irrigated with COMBs (1.6 to 2.4 units) or KPME (3.0 units). The greater reduction in SAR in gypsum-amended soils irrigated with COMBs was not surprising as these treatments contained additional DW that would have reduced the amounts of Na^+, Ca^{2+}, and Mg^{2+} applied. However, the greater decrease in SAR between gypsum-amended soils irrigated with KPME compared to those irrigated with WAS can be attributed to the much larger concentration of HCO_3^- in the WAS compared to that of the KPME. Even though KPME had a greater concentration of Na^+ (293.3 mg L^{-1}) compared to WAS (249.0 mg L^{-1}) and less Ca^{2+} and Mg^{2+}, the greater concentration of HCO_3^- likely negated the additional benefits of gypsum application. At the end of the study, there were no significant differences in SAR between non-amended and ash-amended soils.

At the completion of the study soluble Na^+ and Ca^{2+}, in the saturated paste extract, (Table 5.8) were increased because of irrigating with COMBs, KPME, and WAS. Soluble Na^+ was increased by ash but not by gypsum. Averaged across effluent treatments, soluble Na^+ concentration was significantly higher in ash-amended soils compared to both non-amended and gypsum-amended soils; no differences were measured between the latter two sets of soils. Gypsum-amended soils when irrigated with COMB-100 or KPME resulted in lower soluble Na^+, in saturated paste extracts, than those measured in non-amended soils and were lower than those ash-amended. Soluble Ca^{2+}, in saturated paste extracts, was increased in soil irrigated with COMB-25, COMB-50, COMB-100, KPME, and WAS. Across effluents, except for COMB-100, soluble Ca^{2+} measured in gypsum-amended soils was significantly greater than in non-amended but not ash-amended soils. Gypsum as a Ca^{2+} amendment may be better suited in the short term but ash, with lower Ca^{2+} solubility, may provide a long-term source of Ca^{2+}. However, given the short period over which this growth chamber study was conducted, this could not be verified. Soluble Ca^{2+} in gypsum-amended soils irrigated with DW was significantly greater than in both non-amended and ash-amended soils. Soluble Mg^{2+} concentrations were increased in ash-amended soils, except for

DW and COMB-25.

By the end of the study, soluble Cl^- was significantly increased by effluent and amendment type (Table 5.8). Chloride concentrations were higher in COMBs, KPME, and WAS irrigated soils compared to DW; these were further increased by ash. Significant differences in the concentration of Cl^- in the saturated paste extract of soils irrigated with COMB-100 and KPME were measured between non-amended and gypsum-amended soils, and between gypsum- and ash-amended soils. Chloride concentrations in these soils were greater in ash-amended soils compared to non-amended and gypsum-amended soils. Soluble Mg^{2+} concentrations were significantly greater in COMB-25, COMB-50, COMB-100, KPME, and WAS irrigated soils compared to those irrigated with DW. Soluble SO_4^{2-} concentrations were also affected by irrigation source-by-amendment interactions. Additionally, gypsum-amended soils had higher soluble SO_4^{2-} in the saturated paste extracts than in non-amended soils when irrigated with COMB-25, COMB-50, COMB-100, COMB-100, KPME, and WAS.

5.3 CONCLUSIONS

Application of two Kraft pulp mill effluents, combined and diluted, increased biomass and elemental uptake by winter wheat. Biomass and elemental uptake was further increased by incorporating gypsum and wood ash into the soil. However, plant uptake only accounted for a small percentage of the total elemental loadings applied through the effluent applications. While ash and gypsum increased soluble Ca^{2+} and SO_4^{2-}, in saturated paste extracts, only gypsum significantly reduced soluble Na^+ in the extracts. Concentrations of Cl^- in the soil increased because of ash applications but were comparable between non-amended and gypsum-amended soils. Further, only gypsum reduced SAR in soils irrigated with the various effluent and effluent combinations, but HCO_3^- reduced the effectiveness of gypsum applications, especially in soils irrigated with WAS. The use of wood ash may not be useful in reducing Na^+ related issues because of lower Ca^{2+} solubility, unless acidic soils could be targeted. High Na^+ and HCO_3^- in Kraft pulp mill effluents will limit their use as sources of irrigation water.

Even at high dilution rates and utilizing Ca amendments, the use of Kraft pulp mill effluents as supplemental water sources will be limited. Economic considerations will play a role over the long term as continual applications of Ca amendments will be required to deal with Na-related issues unless Na can be dealt with prior to effluent disposal. Additional research should be conducted to evaluate upstream methods for reducing CO_3^{2-}, HCO_3^-, and Na^+ concentrations in the effluent prior to an end-of-pipe alternative like irrigation. Reducing the pH of the effluent or field applications of elemental S should be evaluated as potential options for dealing with CO_3^{2-} and HCO_3^-. However, applications of amendments like gypsum, phosphogypsum, and elemental S would be short-term and costly.

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Table 5.1. Values of selected chemical properties of the distilled water, combination, and Kraft pulp mill (KPME and WAS) effluents used in the study. Also shown are the theoretical loadings (mg) due to irrigation source applications at 6 mm day^{-1} for soils planted with winter wheat

	[a] Distilled	Kraft	Waste Activated	COMB	Loadings ------------ mg pot^{-1} ------------			
	Water	Pulp mill	Sludge	(WAS/KPME) (50:50)	--------------- 17 L -------------			
Characteristic	(DW)	(KPME)	(WAS)		DW	COMB	KPME	WAS
pH	6.0	7.9	7.2	7.5				
[b] ECw (dS m^{-1})	0.0	1.8	2.1	1.9				
[c] TDS (mg L^{-1})	<1	1.2	1.1	1.2				
HCO_3 (mg L^{-1})	2.5	312.0	715.0	539.0				
CO_3 (mg L^{-1})	2.5	5.0	5.0	5.0				
[d] SAR	0.5	6.9	5.1	5.9				
[e] SAR_{adj}	0.0	9.7	8.4	9.1				
Ca (mg L^{-1})	0.5	112.0	147.0	135.8	8.6	2 321	1 915	2 514
K (mg L^{-1})	0.1	25.6	36.5	32.6	1.7	557	437	625
Mg (mg L^{-1})	0.1	15.0	19.0	17.8	1.7	304	256	325
Na (mg L^{-1})	1.5	293.3	249.0	274.3	25.7	4 690	5 015	4 258
Cl (mg L^{-1})	1.0	173.3	167.8	172.5	17.1	2 950	2 963	2 869
SO_4 (mg L^{-1})	0.5	461.5	155.5	336.5	8.6	5 754	7 892	2 659

[a] DW – Distilled water control; COMB – DW/WAS/KPME Combination; KPME – Kraft Pulp Mill Effluent; WAS - Waste Activated Sludge
[b] ECw - Electrical Conductivity of irrigation source
[c] TDS – Total Dissolved Solids
[d] SAR - Sodium Adsorption Ratio
[e] SAR_{adj} - Adjusted SAR (Ayers and Westcot 1994)'

Table 5.2. Chemical analyses of the soil, gypsum, and wood ash used in the current growth chamber study

	Soil	Gypsum	Wood Ash
pH - $CaCl_2$	5.9	7.9	13.3
$CaCO_3$ Equiv., %	na	39	87
Saturated Paste Extract			
pH	5.8	7.8	13.8
[a]ECe, dS m^{-1}	2.1	3.2	14.3
[b]SAR	0.4	1.5	191
% - Saturation	38	76	174
Ca, mg kg^{-1}	184	463	61
Mg, mg kg^{-1}	22	78	<1
Na, mg kg^{-1}	13	113	7 221
K, mg kg^{-1}	2	30	70 470
Cl, mg kg^{-1}	4	65	3 480
SO_4, mg kg^{-1}	509	1 581	61 596
Available Nutrients			
NO_3, mg kg^{-1}	36	11	197
PO_4, mg kg^{-1}	22	10	2
K, mg kg^{-1}	232	150	54
SO_4, mg kg^{-1}	322	2 040	1 338
B, mg kg^{-1}	1	68	51
Cu, mg kg^{-1}	1	1	5
Fe, mg kg^{-1}	250	18	168
Mn, mg kg^{-1}	18	2	8
Zn, mg kg^{-1}	13	8	93
Total Nutrient Concentration			
P, mg kg^{-1}	na	50	7 530
K, mg kg^{-1}	na	500	68 300
S, mg kg^{-1}	na	135 000	20 400
Ca, mg kg^{-1}	na	184 000	240 000
Mg, mg kg^{-1}	na	13 800	17 700
Na, mg kg^{-1}	na	270	8 700

[a] ECe - Electrical conductivity of saturated paste extracts
[b] SAR - Sodium Adsorption Ratio
na Not available, analyses not conducted

Table 5.3. Composition (%) of the six irrigation treatments

	[a] DW	KPME	WAS	COMB-25	COMB-50	COMB-100
[a] Distilled Water (DW)	100%			75%	50%	
KPME		100%		12.5%	25%	50%
WAS			100%	12.5%	25%	50%

[a] DW – Distilled water control; COMB – DW/WAS/KPME Combination; KPME – Kraft Pulp Mill Effluent; WAS - Waste Activated Sludge

Table 5.4. Mean biomass for the winter wheat at 3 harvests and the overall total

[a] Treatment		----------- BIOMASS (g) -----------			
Irrigation Source	Amendment	1^{st} Cut	2^{nd} Cut	3^{rd} Cut	Total
DW	Control	0.9	0.9	2.2	4.1
DW	Gypsum	0.9	1.0	1.9	3.7
DW	Ash	1.3	1.9	1.9	5.1
COMB-25	Control	0.8	1.4	2.1	4.3
COMB-25	Gypsum	1.4	1.2	2.1	4.7
COMB-25	Ash	1.5	1.9	2.7	6.2
COMB-50	Control	1.0	1.1	2.5	4.5
COMB-50	Gypsum	1.0	1.4	2.4	4.8
COMB-50	Ash	1.6	2.0	3.2	6.8
COMB-100	Control	1.2	1.5	3.6	6.4
COMB-100	Gypsum	1.1	1.6	3.5	6.3
COMB-100	Ash	1.8	2.4	3.8	8.1
KPME	Control	0.8	1.0	1.7	3.5
KPME	Gypsum	0.9	1.0	1.7	3.6
KPME	Ash	1.6	1.7	2.0	5.2
WAS	Control	1.6	2.8	5.4	7.0
WAS	Gypsum	1.4	2.2	5.4	9.0
WAS	Ash	1.8	2.9	5.4	10.1
[b] Amend.					
	Control	1.1	1.5	2.9	5.0
	Gypsum	1.1	1.4	2.8	5.3
	Ash	1.6	2.1	3.2	6.9
[b] Irrig. Source					
	DW	1.1	1.3	2.0	4.3
	COMB-25	1.2	1.5	2.3	5.0
	COMB-50	1.2	1.5	2.7	5.4
	COMB-100	1.4	1.9	3.6	6.9
	KPME	1.1	1.2	1.8	4.1
	WAS	1.6	2.6	5.4	8.7
[c] $HSD_{0.05}$					
	Irrigation Source (IS)	0.4	0.5	0.5	0.9
	Amendment (A)	0.2	0.3	0.3	0.5
	IS x A	ns	ns	ns	ns

[a] DW – Distilled water control; COMB-25, COMB-50, COMB-100 – DW/WAS/KPME Combinations; KPME – Kraft Pulp Mill Effluent; WAS - Waste Activated Sludge

[b] Averages for amendments (control, gypsum, ash) and irrigation sources (DW, COMB-25, COMB-50, COMB-100, KPME, WAS) main factor effects

[c] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

ns = not significant

Table 5.5. Mean tissue concentrations for N, P, K, S, Ca, Mg, and Cl (%) Na and B (mg kg^{-1}) in the 2nd cut of winter wheat

[a] Treatment		N	P	K	S	Ca	Mg	Cl	Na	B
Irrig. Source	Amendment	----------------------------			%	----------------------------			-- mg kg^{-1} --	
DW	Control	5.2	0.25	3.8	0.52	0.49	0.33	0.8	18	8.7
DW	Gypsum	4.8	0.30	4.6	0.61	0.43	0.31	2.4	1 003	11.0
DW	Ash	3.8	0.33	4.6	0.52	0.39	0.25	1.1	937	12.3
COMB-25	Control	4.3	0.37	4.4	0.53	0.61	0.30	2.6	449	6.3
COMB-25	Gypsum	4.8	0.37	4.7	0.57	0.54	0.32	2.1	485	9.3
COMB-25	Ash	4.1	0.41	5.1	0.56	0.47	0.27	2.4	389	9.7
COMB-50	Control	4.7	0.39	4.6	0.57	0.48	0.28	2.5	949	6.0
COMB-50	Gypsum	5.0	0.44	4.8	0.58	0.54	0.33	2.6	742	10.0
COMB-50	Ash	4.1	0.39	5.1	0.55	0.44	0.26	2.3	633	11.3
COMB-100	Control	3.9	0.38	4.5	0.55	0.48	0.29	2.5	1 180	6.7
COMB-100	Gypsum	4.6	0.38	4.9	0.60	0.55	0.30	2.3	1 347	10.7
COMB-100	Ash	3.7	0.38	4.7	0.53	0.53	0.25	2.0	1 246	12.7
KPME	Control	5.3	0.31	4.5	0.65	0.33	0.30	2.6	936	5.0
KPME	Gypsum	4.8	0.32	4.1	0.68	0.54	0.35	0.8	60	17.0
KPME	Ash	4.2	0.30	4.8	0.48	0.48	0.25	1.0	52	11.0
WAS	Control	4.3	0.37	4.5	0.53	0.52	0.27	2.3	1 571	6.0
WAS	Gypsum	4.6	0.40	4.6	0.56	0.57	0.28	2.6	1 580	10.7
WAS	Ash	4.0	0.37	4.8	0.57	0.51	0.25	2.1	1 297	10.7
[b] Amend.										
	Control	4.6	0.35	4.4	0.56	0.49	0.30	2.2	850	6.4
	Gypsum	4.8	0.37	4.6	0.60	0.53	0.32	2.2	869	11.4
	Ash	4.0	0.36	4.9	0.54	0.47	0.25	1.8	759	11.3
[b] Irrig. Source										
	DW	4.6	0.29	4.3	0.55	0.44	0.30	1.4	653	10.7
	COMB-25	4.4	0.38	4.7	0.56	0.54	0.30	2.4	441	8.4
	COMB-50	4.6	0.41	4.8	0.57	0.49	0.29	2.5	774	9.1
	COMB-100	4.1	0.38	4.7	0.56	0.52	0.28	2.3	1 258	10.0
	KPME	4.8	0.31	4.5	0.60	0.45	0.30	1.5	349	11.0
	WAS	4.3	0.38	4.6	0.55	0.53	0.26	2.3	1 482	9.1
[c] $\mathrm{HSD}_{0.05}$										
	Irrigation Source (IS)	ns	0.05	0.3	ns	0.07	0.03	0.5	375	2.5
	Amendment (A)	0.4	ns	0.2	0.05	0.04	0.02	0.3	ns	1.5
	IS x A	ns	ns	0.6	ns	0.15	ns	1.0	810	5.4

[a] DW – Distilled water control; COMB-25, COMB-50, COMB-100 – DW/WAS/KPME Combinations; KPME – Kraft Pulp Mill Effluent; WAS - Waste Activated Sludge

[b] Averages for amendments (control, gypsum, ash) and irrigation sources (DW, COMB-25, COMB-50, COMB-100, KPME, WAS) main factor effects

[c] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

ns = not significant

Table 5.6. Mean tissue concentrations for N, P, K, S, Ca, Mg, and Cl (%) Na and B (mg kg^{-1}) in the 3rd cut of winter wheat

[a]Treatment		N	P	K	S	Ca	Mg	Cl	Na	B
Irrig. Source	Amendment	%							-- mg kg^{-1} --	
DW	Control	1.4	0.13	1.7	0.22	0.55	0.23	0.7	32	6.3
DW	Gypsum	1.3	0.14	1.6	0.69	0.66	0.27	0.5	21	12.0
DW	Ash	1.1	0.18	1.6	0.31	0.71	0.25	0.7	195	22.3
COMB-25	Control	1.9	0.29	2.6	0.67	0.76	0.27	1.2	642	8.3
COMB-25	Gypsum	1.6	0.21	2.3	0.54	0.72	0.26	1.1	598	9.7
COMB-25	Ash	1.5	0.24	2.2	0.46	0.62	0.24	0.8	508	12.3
COMB-50	Control	1.8	0.29	2.4	0.62	0.64	0.24	1.2	1 477	6.0
COMB-50	Gypsum	1.7	0.29	2.3	0.68	0.73	0.27	1.1	1 370	11.3
COMB-50	Ash	1.7	0.32	2.6	0.57	0.60	0.24	0.8	1 357	12.0
COMB-100	Control	2.1	0.29	2.5	0.64	0.72	0.27	1.6	3 720	2.7
COMB-100	Gypsum	2.0	0.29	2.5	0.56	0.69	0.27	1.4	2 510	6.3
COMB-100	Ash	2.0	0.33	2.6	0.51	0.62	0.26	1.2	2 930	5.3
KPME	Control	1.2	0.15	1.7	0.43	0.47	0.20	1.0	1 280	3.7
KPME	Gypsum	1.2	0.16	1.8	0.48	0.50	0.22	0.8	1 227	8.0
KPME	Ash	1.3	0.21	1.9	0.41	0.57	0.24	0.7	1 667	11.7
WAS	Control	2.9	0.33	2.8	0.48	0.73	0.31	2.3	4 120	3.7
WAS	Gypsum	2.5	0.30	2.2	0.39	0.66	0.29	2.1	4 177	8.3
WAS	Ash	2.5	0.36	2.9	0.45	0.61	0.28	2.0	3 520	9.0
[b] Amend.										
	Control	1.9	0.25	2.3	0.51	0.64	0.25	1.3	1 878	5.1
	Gypsum	1.7	0.23	2.1	0.56	0.66	0.26	1.2	1 651	9.3
	Ash	1.7	0.27	2.3	0.45	0.62	0.25	1.0	1 696	12.1
[b] Irrig. Source										
	DW	1.2	0.15	1.6	0.41	0.64	0.25	0.6	83	13.6
	COMB-25	1.6	0.25	2.4	0.56	0.70	0.26	1.1	583	10.1
	COMB-50	1.7	0.30	2.4	0.62	0.66	0.25	1.0	1 401	9.8
	COMB-100	2.0	0.30	2.5	0.57	0.68	0.27	1.4	3 053	4.8
	KPME	1.3	0.17	1.8	0.44	0.51	0.22	0.8	1 391	7.8
	WAS	2.6	0.33	2.6	0.44	0.67	0.29	2.1	3 939	7.0
[b]HSD$_{0.05}$										
	Irrigation Source (IS)	0.3	0.05	0.3	0.12	0.11	0.03	0.3	555	6.0
	Amendment (A)	0.2	0.03	0.2	0.07	ns	ns	0.2	ns	3.5
	IS x A	ns	ns	0.7	0.26	0.24	ns	ns	ns	ns

[a] DW – Distilled water control; COMB-25, COMB-50, COMB-100 – DW/WAS/KPME Combinations; KPME – Kraft Pulp Mill Effluent; WAS - Waste Activated Sludge

[b] Averages for amendments (control, gypsum, ash) and irrigation sources (DW, COMB-25, COMB-50, COMB-100, KPME, WAS) main factor effects

[c] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

ns = not significant

Table 5.7. Mean soil NO_3, PO_4, K, SO_4, and B (mg kg^{-1}) in the soil after 91 days of irrigation source applications to soil planted with winter wheat

[a] Treatment Irrig. Source	Amendment	NO_3	PO_4	K	SO_4	B
				mg kg^{-1}		
DW	Control	0.88	18.2	79.5	12.6	0.31
DW	Gypsum	0.41	4.4	32.6	556.9	0.49
DW	Ash	0.92	9.2	117.4	42.6	0.51
COMB-25	Control	1.16	8.5	55.8	100.0	0.47
COMB-25	Gypsum	0.90	7.2	49.5	696.7	0.62
COMB-25	Ash	0.95	13.0	124.3	130.2	0.59
COMB-50	Control	1.80	10.5	59.5	139.2	0.44
COMB-50	Gypsum	1.05	10.6	56.1	776.4	0.69
COMB-50	Ash	1.28	23.2	143.9	233.5	0.74
COMB-100	Control	1.18	13.6	56.4	300.5	0.41
COMB-100	Gypsum	0.77	12.1	55.9	856.4	0.57
COMB-100	Ash	0.57	19.7	139.2	382.6	0.57
KPME	Control	0.67	5.1	44.9	227.7	0.28
KPME	Gypsum	0.31	5.6	54.1	812.8	0.46
KPME	Ash	0.62	11.0	161.3	316.9	0.49
WAS	Control	0.87	19.7	49.2	309.0	0.46
WAS	Gypsum	0.59	19.3	60.3	949.6	0.78
WAS	Ash	0.91	27.6	147.8	355.7	0.91
[b] Amend.						
	Control	0.88	17.3	139.0	243.6	0.63
	Gypsum	1.09	12.6	57.6	181.5	0.40
	Ash	0.67	9.9	51.4	774.8	0.60
[b] Irrig. Source						
	DW	0.84	15.1	83.9	513.2	0.52
	COMB-25	1.00	9.6	76.5	309.0	0.56
	COMB-50	1.38	14.8	86.5	383.0	0.62
	COMB-100	0.74	10.6	76.5	204.0	0.44
	KPME	0.53	7.3	86.8	452.5	0.41
	WAS	0.79	22.2	85.8	538.1	0.72
[b] $HSD_{0.05}$						
	Irrigation Source (IS)	0.56	9.1	ns	72.9	0.12
	Amendment (A)	0.32	5.2	15.7	41.8	0.07
	IS x A	ns	ns	ns	ns	ns

[a] DW – Distilled water control; COMB-25, COMB-50, COMB-100 – DW/WAS/KPME Combinations; KPME – Kraft Pulp Mill Effluent; WAS - Waste Activated Sludge

[b] Averages for amendments (control, gypsum, ash) and irrigation sources (DW, COMB-25, COMB-50, COMB-100, KPME, WAS) main factor effects

[c] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

ns = not significant

Table 5.8. Mean soil pH, EC, SAR, and soluble Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, and SO_4^{2-} (mg L^{-1}) in the soil after 91 days of irrigation source applications to soil planted with winter wheat

[a] Treatment Irrig. Source	Amendment	pH	[b] ECe	[c] SAR	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}
			dS m^{-1}		----------	----------	mg L^{-1}	----------	----------	----------
DW	Control	6.1	0.7	1.0	16	45	6	7	43	115
DW	Gypsum	6.3	2.7	0.3	13	285	37	7	711	1 873
DW	Ash	7.5	1.4	1.5	35	89	14	13	164	439
COMB-25	Control	6.5	2.6	5.5	152	120	15	78	307	775
COMB-25	Gypsum	6.6	3.9	3.9	162	292	32	67	818	2 153
COMB-25	Ash	7.2	3.4	5.7	198	181	27	114	447	1 113
COMB-50	Control	6.7	4.1	8.9	285	168	21	170	571	1 473
COMB-50	Gypsum	6.8	4.9	6.7	279	288	35	142	920	2 400
COMB-50	Ash	7.2	5.2	10.2	403	227	39	231	820	2 000
COMB-100	Control	6.8	6.4	13.9	543	241	30	326	1 043	2 627
COMB-100	Gypsum	6.8	6.1	11.5	507	294	39	277	1 181	2 857
COMB-100	Ash	7.3	7.3	14.1	614	285	44	393	1 137	2 797
KPME	Control	6.2	6.1	13.0	480	217	31	320	910	2 360
KPME	Gypsum	6.6	6.1	10.0	437	301	42	260	1 128	2 847
KPME	Ash	7.4	7.1	13.7	551	250	43	376	1 038	2 773
WAS	Control	6.7	6.8	13.6	575	280	35	318	1 052	2 630
WAS	Gypsum	6.8	7.2	13.0	597	326	40	307	1 226	2 990
WAS	Ash	7.2	7.2	13.9	624	294	49	326	1 061	2 613
[d] Amend.										
	Control	7.3	5.3	9.9	404	221	36	242	778	1663
	Gypsum	6.5	4.4	9.3	342	178	23	203	654	2520
	Ash	6.7	5.2	7.6	333	298	37	177	997	1956
[d] Irrig. Source										
	DW	7.0	6.6	13.2	555	273	38	332	1120	809
	COMB-25	6.8	3.3	5.0	171	197	25	87	524	1 347
	COMB-50	6.9	4.7	8.6	323	228	31	181	770	1 958
	COMB-100	6.6	1.6	0.9	21	140	19	9	306	2 760
	KPME	6.7	6.4	12.2	489	256	38	319	1 026	2 660
	WAS	6.9	7.1	13.5	599	300	42	317	1 113	2 744
[e] $HSD_{0.05}$										
	Irrigation Source (IS)	0.2	0.6	1.1	64	36	7	53	107	256
	Amendment (A)	0.1	0.3	0.6	37	21	4	30	61	123
	IS x A	0.5	1.3	ns	ns	77	15	ns	231	453

[a] DW – Distilled water control; COMB-25, COMB-50, COMB-100 – DW/WAS/KPME Combinations; KPME – Kraft Pulp Mill Effluent; WAS - Waste Activated Sludge

[b] Averages for amendments (control, gypsum, ash) and irrigation sources (DW, COMB-25, COMB-50, COMB-100, KPME, WAS) main factor effects

[c] HSD - Tukey's Honestly Significant Difference (0.05) calculated for main factor and main factor interactions for mean separations.

ns = not significant

6. *Irrigating Soil With Kraft Pulp Mill Effluent Under Field Conditions*

Historically, effluents have been discharged to surface water for disposal but alternatives need to be evaluated as regulatory guidelines become more stringent (Speir 2002). Agroforestry systems have the potential to renovate municipal and industrial effluents. Research at northern latitudes incorporating effluent as a source of irrigation water has been limited. The integration or combination of agricultural with forest crops can allow more efficient use of water and nutrient resources through integrated management. Increasing urban and industrial expansion and competition for land makes the need for protection and preservation of potable water quality ever so important. As a result, an evaluation is required of where and how effectively these water sources are being used.

Effluents could serve as a source of water and nutrients for crop production, thereby reducing the demand for potable water for irrigation water and fertilizer inputs (Speir 2002). Tertiary treatment by agricultural or tree crops could serve as a value-added alternative to discharge to surface water courses with irrigated crops being used for bio-energy or bioproduct production provided effluent is applied under appropriate conditions. Irrigating non-food crops significantly reduces health related concerns often associated with irrigation of food crops. However, one of the major concerns with effluent irrigation is the accumulation of soluble salts in the soil and the direct impacts on crop growth, nutrient uptake, and soil nutrient availability. Tolerances of selected crops to exchangeable sodium and salinity are shown in Table 8.1 and Table 8.2 (Appendix – A), while Table 9.1 and Table 9.2 (Appendix – B) show some of the guidelines and parameters which should be considered when considering effluents as an irrigation source. The use of effluents for irrigation can result in nutrient imbalances and adverse changes in soil chemical (e.g., soluble salts) and physical (e.g., dispersion and reduced infiltration) properties, negatively affecting cropping systems (Balks et al. 1998; Halliwell et al. 2001).

Saline and sodic effluents when used as sources of irrigation water require careful management and monitoring of both the soil SAR and electrical conductivity (EC) (Rengasamy et al. 1984; Rengasamy and Olsson 1993), as both can impact soil properties like infiltration rate. Sufficient leaching must occur when using saline effluents in order to prevent salt accumulation within the rooting zone. Effluents with elevated SAR used for irrigation should also have elevated ECs as saline waters can promote stability of soil structure instead of an unstable soil structure due to Na-induced dispersion (Letey 1993; Buckland et al. 2002; Tillman and Surapaneni 2002). When used for irrigation, effluents with elevated SAR coupled with a low to moderate electrical conductivity (EC) require close monitoring; this is the case with Kraft pulp mill effluents (KPME). KPMEs contain high concentrations of dissolved sodium (Na^+), sulphate (SO_4^{2-}), chloride (Cl^{2-}), and bicarbonate (HCO_3^-), and high SAR. As a result, the chemical composition of KPME effluents can determine the impact these effluents will have on irrigated soils. For example, high concentrations of HCO_3^{2-} in the effluent will cause calcium (Ca^{2+}) in the effluent and in the soil to precipitate out as $CaCO_3$, removing Ca^{2+} and further increasing the deleterious effect of Na^+ on the soil (Ayers and Westcot 1994; Halliwell et al. 2001). The resulting increase of Na^+ elevates SAR (Balks et al. 1998; Halliwell et al. 2001; Sparling et al. 2001), resulting in increased soil dispersion, reduced hydraulic conductivity, and reduced infiltration capacity (Magesan et al. 1999). In addition, reduced osmotic potentials lead to drought-like conditions for plants (Shani and Dudley 2001), reducing their productivity.

Supplemental irrigation strategies using pulp mill effluents could be adopted in sub-humid regions. Under a supplemental irrigation strategy, effluents would provide a source of water during periods of crop water deficits. Precipitation during early stages of the growing season and after harvest can flush salts from the root zone, reducing salt stress (Sharma et al. 1994). According to Sharma et al. (1994), cyclic irrigation allows precipitation received at the site to reduce salinity or sodicity caused by effluent irrigation. This process allows effluents or poorer quality drainage waters to supplement the crop water requirement without yield reductions or soil degradation. Coupling cyclic irrigation strategies with intercropping, organic matter or calcium amendments may also reduce soil sodicity further. Decomposition of organic matter helps mobilize Ca^{2+} by increasing the concentration of organic acids and CO_2 in the soil solution increasing the solubility of $CaCO_3$ (Sekhon and Bajwa 1993; Mishra et al. 2004).

The objectives of this field study were to determine what short term impacts precipitation would have on elemental loadings from irrigated KPME applications and what effect it would have on the same parameters, after subsequent years without irrigation.

6.1 MATERIALS AND METHODS

6.1.1 Experimental Design and Treatments

The field site is located in the Mid Boreal Mixedwood Ecoregion south of a pulp mill operated by Alberta-Pacific Forest Industries at 54°55 latitude and 112°52' longitude, approximately 200 km northeast of Edmonton, Alberta, Canada. The region is sub-humid receiving an average 503 mm of precipitation annually, with approximately 65% occurring during the May through September growing season; Canadian Climate Normals (CCN) from the region are summarized in Table 6.1 (Environment Canada 2007a). The Environment Canada Meteorological station at Athabasca is located 42.6 km west of the research site.

The site is 2.5 ha in size, consisting of a strip-split-split-plot design with four complete replicates (Figure 6.1). The study contained three irrigation treatments: a non-irrigated control, water, and Kraft pulp mill effluent (KPME). Irrigation treatment was the main factor laid out in strips, with vegetation comprising one of the splits within each irrigation treatment (Figure 6.2). The second split was assigned based on the uniformity of coverage by the irrigation system determined by catch cans placed throughout each irrigated plot. The two vegetation treatments consisted of hybrid poplar only and hybrid poplar intercropped with a mixture of timothy (*Phleum pratense* L. cv. Climax 00-8031147-401, Lot No. 1397-00-46-3, Ref W1-068), and alsike clover (*Trifolium hybridum* L. cv. Aurora; Lot No. 846-7-054826 P24-02) and irrigated simultaneously. The forage mixture was seeded during the last week of May 2002 (Yr-1) using a Landpride Solid Stand Seeder at a rate of 6.3 kg ha^{-1}. Hybrid poplar cuttings 20 cm in length were soaked in water for 72 hours and then hand planted at a spacing of 3.0 m between rows and 2.0 m within rows. Each plot was approximately 144 m^2 and consisted of four rows of hybrid poplar trees; each row contained five trees. Weeds were manually controlled. Once forages had been sampled for biomass, they were harvested and plant material from the hybrid poplar plus forage treatment was removed from the site; trees were not harvested during the study. The vegetation treatment containing only hybrid poplar was rotovated twice during each growing season. Eleven piezometers were installed to a depth of 4 m at the site to measure fluctuations in groundwater quality during the study and allow collection of water samples for analyses.

Effluent rates were selected based on an Agricultural Feasibility Report conducted for the field site, which estimated the water requirement of a young hybrid poplar plantation to be 375 mm (Proudfoot 2000). Over an 18-wk (early May to mid September) irrigation schedule, this equates to just less than 3 mm d^{-1}; this was the rate selected for the field study. During the five-year period the study was conducted, a total of 300 mm of effluent or water was applied: 90 mm in year 1 (Yr-1; 2002), 90 mm in year 2 (Yr-2; 2003), and 120 mm in year 3 (Yr-3; 2004) of effluent or water to supplement annual precipitation. No irrigation occurred in year 4 (Yr-4; 2005) or year 5 (Yr-5; 2006). Irrigation was applied during the night for the first three years of the study. Irrigation did not take place during windy or rainy conditions. Effluent was collected from the final outflow prior to discharging to the Athabasca River and water, comprised of primarily precipitation and runoff from the site, was taken from a retention pond located at the millsite. Separate irrigation systems were utilized to prevent cross contamination of sources.

Research plots were located on the north side of a line-source irrigation system, which provided effluent and water to a solid set sprinkler system with four 1.9-cm Nelson F-33 double nozzle sprinklers on each lateral. The larger nozzle on each sprinkler contained a 5-gpm Flow Control Nozzle® (FCN) and the smaller nozzle contained a plug to prevent flow. Sprinklers on each lateral were mounted on 60-cm risers spaced 12.0 m apart.

Eleven catch cans were placed within a research plot to determine application depths (Figure 6.2). One catch can was placed adjacent to each of two sprinklers with three more catch cans placed on the side closest to the sprinkler, one each at the base of the first, third, and fifth tree in each of the three tree rows adjacent to the lateral. Depths measured through the plot were divided by the amount received adjacent to each sprinkler, multiplied by 100%, and expressed as uniformity values. The uniformity values where soil samples were collected averaged from 67% for soil samples taken furthest from the sprinkler to 97% for soil samples collected adjacent or near to the sprinkler.

6.1.2 Effluent and Water Analyses

Effluents and water was during each irrigation event and later analyzed by EnviroTest Laboratories (Edmonton, AB) (Table 6.2). Effluent and water samples were analyzed using methods outlined by the American Public Health Association (1998) for pH (Method 4500-H), electrical conductivity (EC, Method 2510), alkalinity (Method 2320), total dissolved solids (TDS), total organic carbon (TOC, Method 5310B) and total Kjeldahl nitrogen (TKN, Method 4500N-C). Method 3120B ICP-OES was used to quantify various ions in solution (i.e., sulphate (SO_4^{2-}), calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), and sodium (Na^+)). Chloride was determined colorimetrically (Method 4500; APHA 1998).

When irrigation treatments were being applied, effluent and water were hauled continuously over a 12- to 14-hour period to the research site and stored separately in two 13-m^3 fiberglass tanks. Effluent and water samples collected each year were analyzed for select chemical parameters (Table 6.2), according to standard methods for water and effluent analysis (APHA

1998). Water and effluents were analyzed by EnviroTest Laboratories (Calgary, Alberta).

6.1.3 Soil Moisture

In the first year of the study, two 1-m aluminum access tubes were installed in the second and third tree rows at one of four locations within the row within each plot to monitor volumetric soil moisture using a Campbell Pacific Nuclear Model 503DR Hydroprobe neutron moisture meter. Soil moisture was measured every two weeks during the season. Readings were taken at 10-cm depth increments beginning at 15 cm below the surface. Volumetric soil moisture measurements were then used to determine total soil water in the upper 40 cm (TSW40) of the soil profile.

Six-point soil water retention curves were created using the analyses from baseline soil samples (n=11) collected to a depth of 1.0 m using pressure plate apparatus at pressures of 5, 10, 33, 100, 300, and 1500 kPa (Topp et al. 1993). Field capacity (FC) and wilting point (WP) determinations were made for the 0-20, 20-40, 40-60, 60-80, and 80-100 cm depth increments. Field capacity (112 mm) was then determined for the 0-40 cm depth increment using the water contents of the samples analyzed from the 0-20 cm depth increment samples at 33 kPa and 10 kPa for samples analyzed from the 20-40 cm depth increment. Wilting point (38.2 mm) was calculated based on the water content of samples at 1500 kPa for both depth increments. The plant available water (PAW; 73.8 mm) was then calculated as the difference between water content at field capacity (FC) and that at the wilting point (WP); the general rule is to irrigate when soil water reaches 50% PAW. Total soil water (TSW40) to 40 cm was calculated by multiplying the volumetric moisture contents (%, VMC) at 15 (VMC_{15}), 25 (VMC_{25}), and 35 (VMC_{35}) cm and multiplying 200, 100, and 100 mm, respectively, and then summing the three values (Equation 6.1).

Equation 6.1. $$\mathbf{TSW = VMC \times Depth\ (mm)}$$

6.1.4 Soil Analyses

The area where the field study was established contains Brunisols, Orthic Gray Luvisols, and Humic Eluviated Gleysols (70% Tawatinaw series, O.GL; 20% Codesa Complex series, B and O.GL; and 10% Mapova series, H.EGL) based on the soil survey of the Tawatinaw map sheet (83-I) (Kjearsgaard 1972). The soils at the study site were classified as Eluviated Dystric Brunisols in the Agriculture Feasibility Study (Proudfoot 2000). The site slopes west and northwest with 1 to 5% slope and undulating topography. The field study was conducted on a slightly acidic, loam to sandy loam Eluviated Dystric Brunisol (Table 6.2) with low SAR and ECe, but high Ca^{2+} and SO_4^{2-}. Soil samples were collected during the last week of October in 2002 (Yr-1) as a baseline; results are shown in Table 6.2, with subsequent samples collected the last week of October in 2003 (Yr-2), 2004 (Yr-3), 2005 (Yr-4), and 2006 (Yr-5).

During Yr-1, two sampling areas were identified and sampled separately in each treatment based on the uniformity of water or effluent being applied by the sprinkler system (Figure 6.2). Each area was sampled separately to a depth of 1.0 m in the following depth increments: 0-20, 20-40, 40-60, 60-80, and 80-100 cm. The hydrometer method was used for soil texture analyses (Sheldrick and Wang, 1993). Soil analyses, conducted by EnviroTest Laboratories (Edmonton, AB; now ALS Laboratories) was conducted on saturated paste extracts to determine soil pH and ECe (Hendershot et al. 1993), SAR, soluble K^+, Na^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-} (Janzen 1993) and soluble Cl^- (APHA 1998). Deionized water was added to saturate the soil. After sitting overnight, an extract was obtained by vacuum filtration and individual cations (Ca^{2+}, K^+, Mg^{2+}, and Na^+) and anions (SO_4^{2-}) were determined with an Inductively Coupled Plasma Optical Emission Spectrophotometer (ICP-OES) (Janzen 1993) and EC and pH measured using their respective meters. Soluble Cl^- was analyzed using the mercuric thiocyanate colorimetric method and quantified using a Technicon Autoanalyzer (APHA 1998).

6.1.5 Statistical Analyses

The study was conducted over a five-year period and consisted of a strip-split-split-plot design. The study had three irrigation treatments that included a non-irrigated treatment, a treatment irrigated with water, and a treatment irrigated with KPME. Each irrigation treatment was split into two vegetation treatments containing either hybrid poplar grown alone or hybrid poplar intercropped with timothy and alsike clover. Soil moisture data were compared using means and standard errors and not subjected to repeated measures analyses. Soil chemical analyses were analyzed with the PROC MIXED procedure of SAS (Littel et al. 1996). Variances were notably heterogeneous among depths. Therefore, data were analyzed separately by depth with the PROC MIXED procedure of SAS (Littel et al. 1996). The effect of replicate (R) was considered random, and the effects of the year (Y), uniformity (U), and irrigation source treatments (IS) were considered fixed. A model parameterized to account for repeated measurements across years for each experimental unit (replicate by uniformity by applied treatment combinations) did not consistently or notably improve model fit (corrected Akaike's criterion). Therefore, final statistical analysis did not account for repeated measurements. Where significant treatment effects were determined an $LSD_{0.05}$ was calculated to provide a method of comparing means and measure of precision. Data was then collated for each year-by-depth combination to compare means across the applied treatment combinations (Table 6.8). Only when the F test was significant were statistical differences among means determined.

6.2 RESULTS

6.2.1 Climatic Data

Compared to the Environment Canada (2007b) data (Table 6.1), data collected from the study site (not provided) from 2003 to 2005 during the growing season showed: air temperatures 1.5 to 4% lower at the study site, precipitation received at the site was 57.5, 30.4, and 17.2% lower during this period, and the number of growing degree days was 6.7% higher in 2003, but 7.4 and 6.6% lower in 2004 and 2005, respectively. For the same period indicated: air temperatures were 5.3 to 27.3% lower, the amount of precipitation received was 28.4 and 8.3% lower in 2003 and 2004, but 11.1% higher in 2005, and the number of growing degree days were 0.3 to 10.1% higher compared to annual data from Environment Canada (2007b).

Compared to the long term average (CCN 2007a) data during the growing season from 2002 to 2006 from the Environment Canada site (2007b), air temperatures were comparable in 2002, 7.3, 6.2, 4.4, and 15.7% lower from 2003 to 2006; precipitation received at the site was 40, 7.2, and 19.8% lower in 2002, 2003, and 2005 and 10.7 and 17.9% higher in 2004 and 2006, and the number of growing degree days was 2% higher in 2002, but 4.3, 7.9, 7.6, and 12.6% lower from 2003 to 2006, respectively. Annual data comparisons showed air temperatures were 2.7 and 4.3% higher in 2004 to 2005 than the CCNs, but 12.5 to 31.8% lower in 2002, 2003, and 2006. Precipitation received was 13.4 and 4.7% higher in 2004 and 2006, but 32.7, 2.4, and 31.4% less in 2002, 2003, and 2005; and the number of growing degree days was 1.6 to 16.3% lower from 2002 to 2006, than the CCNs.

Based on Environment Canada (2007b) data the total amount of effluent or water applied through irrigation represented 15 to 21% of the total precipitation received from Yr-1 to Yr-3. By the end of the study, the amount of effluent and water applied through irrigation at the site represented only 11.7% of the total moisture received.

6.2.2 *Irrigation Sources*

SAR_{adj} (11.0) and EC (2.0 dS m^{-1}) of the study KPME were slightly lower than those of the KPME used in the two previous studies (Patterson et al. 2008a; Patterson et al. 2008b) but similar to long-term averages of 10.5 SAR_{adj} and 2 dS m^{-1} EC for KPME produced in the mill which supplied the effluent. SAR were adjusted (SAR_{adj}) according to Ayers and Westcot (1994) to account for high HCO_3 concentrations. According to FAO water quality standards (Ayers and Westcot1994), KPME used in this study falls along the border of 'Potentially Hazardous' and 'Safe' (Patterson et al. 2008a; Patterson et al. 2008b). The SAR_{adj} is slightly too high for routine irrigation and would require monitoring according to the classification scheme of Steppuhn and Curtin (1993).

Data for long-term data for KPME and the four irrigation sources used in this experiment were plotted in Piper diagrams (Figure 10.1, Figure 10.2, and Figure 10.4; Appendix – C). Plotting long-term KPME data in the Piper Diagrams show, the dominant cations being Na^+ + K^+ (~60-75%) in solution followed by Ca^{2+} (~30-35%), and Mg^{2+} at (~5%), while SO_4^{2-} (~45-65%) were the dominant anion in solution followed by HCO_3^- + CO_3^{2-} ranged from (~20-35%), and Cl^- (15-25%) (Figure 10.1). The major cations in solution of the control were dominated by Ca^{2+} (~48%), Mg^{2+} (~30%), followed by Na^+ + K^+ (~22%), while anions were dominated by HCO_3^- + CO_3^{2-} (53%), SO_4^{2-} (~45%), and Cl^- (~2%) (Figure 10.2). Data collected from the field study component for KPME (Figure 10.4) were comparable to the long-term values.

6.2.3 *Total Soil Water*

Total soil water to 40 cm (TSW40) in cultivated soils receiving no irrigation in Yr-1 gradually increased from mid-July to early August after which TSW40 began to decrease (Figure 6.3). TSW40 of soils seeded with the timothy and alsike clover mixture steadily decreased from early July to the end of September with only a slight increase in TSW40 by early October in Yr-1.

In Yr-2, TSW40 fluctuated early in the season and remained between 50% of plant available water (PAW) and field capacity (FC) until early to mid-July, when it began to decrease. The TSW40 stabilized slightly from late July to early August most likely due to the irrigation events that occurred at this time. Total soil water began to decline later in the season by September when it dropped below wilting point (WP). In Yr-3 TSW declined slightly at the start of the season to close to the WP but increased from early to mid-July where it remained between 50-75% of PAW for the remainder of the growing season. In Yr-4, with no irrigation, TSW40 increased from the start of the season and was above FC briefly in early August, after which it declined. Total soil water in the two vegetation treatments remained similar in all 4 growing seasons (Figure 6.3, Figure 6.4, and Figure 6.5).

TSW40 in plots irrigated with either water (Figure 6.4) or effluent (Figure 6.5) in Yr-1 remained at 50% PAW until late September. Irrigated treatments in Yr-2 remained above 50% PAW until early September when TSW40 decreased and remained between 50% PAW and WP. This was the only growing season (Yr-2), other than the start of Yr-4, when TSW40 approached WP for irrigated treatments. From Yr-3 to Yr-4, TSW40 remained between 50% PAW and FC. Trends in TSW40 for treatments irrigated with water were similar to those irrigated with KPME in all four years. For the majority of the growing season in all four years TSW40 remained between 50-75% PAW so plants still had access to 37 to 55 mm of plant available water.

6.2.4 Soil Chemistry

Treatment, depth, year, and uniformity and their respective interactions resulted in significant effects on pH, ECe, SAR, soluble Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, and SO_4^{2-} measured in the saturated paste extracts (Table 6.3 to Table 6.7). During the study for all depth increments across years, the soils irrigated with KPME had saturated paste extract pH values which were significantly greater than those measured in soils irrigated with water (data not shown). However the, differences were <0.25 pH units, and soil pH remained <6.5. Soils that were not irrigated showed no significant differences in pH from either the KPME or water irrigation treatments, except for the 40-60 cm depth increment of the KPME irrigation treatment and the 80-100 cm depth increment of the water irrigation treatment.

Kraft pulp mill effluents contain high concentrations of HCO_3^- (330.0 mg L^{-1}), Na^+ (334.6 mg L^{-1}), SO_4^{2-} (593 mg L^{-1}), and Cl^- (139.9 mg L^{-1}) (Table 6.2). The application of KPME as a source of irrigation water for three years increased soluble Na^+ and SAR (2004; Figure 6.6), which then remained elevated relative to the control even after two years of no irrigation (2005 and 2006; Figure 6.6). Soluble Na^+ in the saturated paste extracts in the surface depth increment was greatest in soils after two years. Peak SAR did not occur until the following year (i.e., 0-20 cm; Figure 6.6). By the end of the study, SAR values, of saturated paste extracts, were nearly 3 times greater and soluble Na levels, in the extracts, were 4.5 times greater than the corresponding values in the non-irrigated or water treatments. Soluble Na^+, of the saturated paste extracts, was significantly greater in soils irrigated with KPME than in the non-irrigated or water irrigated treatments in the top two depth increments of Yr-2. From Yr-3 to Yr-5 soluble Na^+ was also significantly greater in KPME irrigated soils in the 40-60 cm depth increment as well, but not until Yr-5 for SAR. Between Yr-3 and Yr-4, SAR of KPME irrigated plots decreased 20% in the 0-20 depth increment. In the lower depth increments soil solution SAR increased 18% (20-40 cm), 38% (40-60 cm), and 32% (60-80 cm). In Yr-5, a further decrease in SAR in KPME irrigated plots of 26% was measured in the 0-20 cm depth increment, while increases of 4, 24, and 12% were measured in the 20-40, 40-60, and 60-80 cm depth increments, respectively. By Yr-4, soluble Na^+, of the saturated paste extracts, of soil irrigated with KPME was significantly greater than in the non-irrigated and water irrigated soils in the 60-80 cm depth increment, but this was less evident in Yr-5. Between Yr-3 and Yr-4, in the 0-20 depth increment soluble Na^+ decreased 3%, with increases of 12, 26, and 42% measured in 20-40, 40-60, and 60-80 cm depth increments. Soluble Na^+ decreased an additional 24% from Yr-4 to Yr-5 in the 0-20 cm depth increment with additional decreases in Na^+ of 13, 10, and 21% measured in the 20-40, 40-60, and 60-80 cm depth increments, respectively. No significant differences in SAR or soluble Na^+ were observed between non-irrigated and water irrigated treatments. The type of vegetative cover also affected SAR and soluble Na^+; areas planted to hybrid poplar had lower SAR but greater soluble Na^+ than the corresponding treatments planted with hybrid poplar and forage mixture (data not shown).

The application of KPME significantly increased soluble Ca^{2+} and soluble Mg^{2+}, of the saturated paste extracts, by the end of Yr-2 in the 0-20 and 20-40 cm depth increments (Figure 6.7). However, from Yr-3 to Yr-5 no significant differences for soluble Ca^{2+} or Mg^{2+} were measured among any of the treatments within the 0-20 cm depth increment. Soil irrigated with KPME had significantly greater soluble Ca^{2+} and Mg^{2+}, in the saturated paste extracts, of soils sampled from the lower depth increments (i.e., 20-100 cm) than either the non-irrigated or water irrigated treatments; except for Yr-5 in the 20-40 and 40-60 cm depth increments. Soluble Ca^{2+} decreased 85 and 38% between Yr-2 and Yr-3 in the 0-20 and 20-40 cm depth increments, once irrigation stopped soluble Ca^{2+} increased 70% in the 0-20 cm depth increment in Yr-4 in soils irrigated with KPME and increased an additional 62% by Yr-5. In the lower depth increments, these changes ranged from -31 to 4% in the 20-80 cm depth increment. Between Yr-4 and Yr-5 in the 20-40, 40-60, 60-80 cm depth increments soluble Ca^{2+} decreased by 6, 28, and 31%, respectively. No significant differences in soluble Ca^{2+} or Mg^{2+}, in the saturated paste extracts, were measured between the non-irrigated and water irrigated treatments in any depth increment. Across depth increments, soluble Ca^{2+} and Mg^{2+} were significantly lower in areas planted with hybrid poplar and forage compared to those containing only hybrid poplar.

Soluble Cl^- and soluble SO_4^{2-}, of the saturated paste extracts, were increased significantly in soils because of irrigation with KPME (Figure 6.8). By the end of Yr-2, concentrations of the two anions were significantly greater than those measured within the non-irrigated and water irrigated treatments to a depth of 60 cm. By the following season, SO_4^{2-}, in saturated paste extracts, of KPME-irrigated soils was significantly greater in almost all depth increments compared to the other two irrigation treatments, with the exception of the 0-20 cm depth increment in soils irrigated with water in Yr-4. Soluble SO_4^{2-} of the saturated paste extracts, decreased 39, 21, 13 and 2% in the 0-20, 20-40, 40-60, and 60-80 cm depth increments, respectively the year after KPME irrigation treatments were stopped, with an additional decrease of 44, 369, 34, and 37% in these depths by the end of Yr-5. Similar changes occurred in the soil profile in these depth increments for soluble Cl^- with an increase of 4% in the 0-20 cm depth increment, but decreases of 16, 20, and 15% respectively between Yr-3 and Yr-4, in the lower increments. Additional decreases in these depth increments of 20, 11, 38, and 50%, respectively, by the end of Yr-5 were measured. No significant differences in soluble Cl^- were measured among any of the irrigation treatments in the 0-20 cm depth increment in Yr-5. Soluble Cl^- in Yr-3 and Yr-4 was significantly greater in all depth increments within KPME irrigated soils relative to the two other irrigation treatments. Only in Yr-5 were there no significant differences measured between KPME irrigated soils and either the control or the water irrigation treatment. This occurred in both the 40-60 and 60-80 cm depth increments of the KPME and non-irrigated treatments. In Yr-5 significant differences in soluble Cl^- were measured between non-irrigated and water irrigated treatments in the 0-20, 20-40, and 80-100 cm depth increments; soluble Cl^- levels were significantly greater in non-irrigated soils than in those of water irrigated treatments. Type of vegetative cover had no significant effects on the levels of soluble Cl^- or SO_4^{2-} within the soil solution (data not shown).

ECe trends were similar to those observed for Cl^- and SO_4^{2-} but remained significantly greater, within soils irrigated with KPME, than those of either of the remaining treatments through to the completion of the study (Figure 6.9). ECe was 0.3 to 10.3 dS m^{-1} lower than those in the previous growth chamber study by Patterson et al. (2008a; 2007b) where distilled water was used to dilute KPME applications. ECe was significantly greater in soils irrigated with KPME in the 0-60 cm depth increments by the end of Yr-2 and all depths by the end of the following season (Yr-3) and remained this way to the completion of the study (Yr-5) (Figure 6.9). ECe was greatest in the 0-20 cm depth increment from the KPME irrigation treatment by the end of Yr-2; while EC in the lower depth increments increased from Yr-2 to Yr-3; it remained constant from Yr-3 to Yr-4 and began to decrease by the end of the study. While significantly affected by the interaction YxDxI, no trends (Figure 6.9) in soluble K^+, of the saturated paste extracts, were evident nor did vegetative cover type (data not shown) have an effect on soluble K^+.

6.3 DISCUSSION

6.3.1 Total Soil Water

Soil water during the first four years of the study for a majority of the treatments, even when no supplemental irrigation was applied, remained close to, or above, 50% PAW. A general rule is to irrigate when TSW drops below 50% PAW. Only during the latter part of the growing season and into the fall did TSW generally drop below this level; indicating supplemental irrigation is only necessary periodically throughout the growing season. The small differences in TSW40 between plots of hybrid poplar, which were cultivated versus those which contained timothy and alsike clover could be expected, given the shallow, dense root systems produced by poplar and timothy (McElroy and Kunelius 1995; Pregitzer and Friend 1996). Soil fertility may have also confounded the crop water use. Since no additional fertilizers were applied, plots could also have been nutrient limited, especially for nitrogen (N) and phosphorus (P). Thus, growth will be limited, and as a result so will plant water use compared to a site which was receiving adequate fertilization. KPME would not likely provide the crop requirements for N or P for optimal production and may have resulted in resource competition between the planted trees, or between the planted trees and forage. The additional water use by the forage crop within the intercropped research plots would have also increased the rate at which soils would have dried out, further promoting the precipitation of Ca^{2+} and Mg^{2+}, forming insoluble $CaCO_3$ and $MgCO_3$.

6.3.2 Soil Chemistry

The application of KPME increased soil extract pH greater than measured in soils irrigated with water. This was most likely due to greater concentrations of Na^+ and HCO_3^- in KPME relative to the water. The soil salinity caused by KPME can be attributed primarily to cations (i.e., Na^+, Ca^{2+}, Mg^{2+}, and K^+) and anions (i.e., Cl^-, SO_4^{2-}, and HCO_3^-). The ion balance of the soil solution indicates additional anions unaccounted for, most likely HCO_3^-. Increased soil pH, observed in KPME irrigated treatments, can be attributed to sites irrigated with effluent which contain greater concentrations of HCO_3^- compared to better quality water sources (Mancino and Pepper 1992) and to the displacement of neutral salts (i.e., Ca^{2+} and Mg^{2+}) with Na^+ (Brady 1990; Howe and Wagner 1999). The increases in pH and Na, in the saturated paste extracts, were also found in previous growth chamber studies conducted by Patterson et al. (2008a; 2007b). ECe and SAR, at the end of the study had a good soil quality rating (Alberta Environment 2001). After three years of irrigation and two subsequent years of no irrigation, ECe and SAR would still be rated as fair to good (Alberta Environment 2001).

By the end of Yr-5 Na in the soil solution of KPME irrigated treatments to a depth of 60 cm still remained significantly higher, compared to the control and water irrigated soils. Sodium in saturate paste extracts has gradually decreased in the surface since the beginning of the study and has increased at lower depths, indicating Na^+ has begun to leach. Evapotranspiration by both the forage and poplar and evaporation would have also enhanced the soil drying process, further contributing to the amount of Ca^{2+} or Mg^{2+} being precipitated out of solution as $CaCO_3$ or $MgCO_3$. The HCO_3^- precipitated Ca^{2+} and Mg^{2+} were removed from solution, shown by the marked decrease in the soil solution of Ca^{2+} and Mg^{2+} by the end of Yr-2. Plant uptake of Ca^{2+} and Mg^{2+} in treatments planted with both hybrid poplar and forage contributed to the increased SAR within this treatment relative to that with only hybrid poplar. Some displaced Na^+ could be attributed to displacement by Ca^{2+} released during the decomposition of organic matter. The solution concentration of Ca^{2+} may have also been increased due to the solubilization of Ca^{2+} from the soil because of the production of organic acids within the rooting zone from the actively growing forages and hybrid poplar (Sekhon and Bajwa 1993; Mishra et al. 2004). Eventually Na^+, which has leached, may form a layer of accumulation below the root zone (Howe and Wagner 1999).

From Yr-3 to Yr-5 soluble Ca^{2+} and Mg^{2+}, of saturated paste extracts, were significantly greater in soils irrigated with KPME than those in the remaining two irrigation treatments. The above average precipitation received in Yr-3 (2004), combined with the coarse texture of the soils at depth may have facilitated the leaching observed for both Ca^{2+} and Mg^{2+}. Additionally, Ca^{2+} and Mg^{2+} that leached could be the result of maintaining surface charges in the soil or simply they could not be adsorbed onto the soil exchange sites. By Yr-5, soluble Ca^{2+} and Mg^{2+}, in saturated paste extracts, from the upper 60 cm were beginning to return to being comparable to the non-irrigated treatment. The addition of Ca^{2+} amendments like gypsum or elemental S may benefit this site and further reduce the increased Na^+ concentrations in the top 40 cm of the soil profile after irrigating with KPME. Gypsum would allow Ca^{2+} to displace the Na^+ on the exchange complex in the soil, allowing for Na^+ to be leached through the profile; elemental S would reduce the soil pH over time, allowing Ca^{2+} present in the soil or that which had precipitated out of solution as $CaCO_3$ to solubilize and displace Na^+ at the exchange sites.

Soluble Cl^- and SO_4^{2-}, in saturated paste extracts, were significantly increased in the upper 60 cm of the soil profile because of KPME applications compared to both non-irrigated and water irrigated treatments. By Yr-3 to the completion of the study, the levels of these two ions in soils irrigated with KPME remained elevated. By Yr-5, only the soluble SO_4^{2-} of saturated paste extracts from the upper 20 cm and soluble Cl^- in the 40-60 and 60-80 cm depth increments of the KPME treatment were comparable to the non-irrigated treatment levels. The anionic nature of Cl^- and SO_4^{2-}, different molecular size and charge, and low background soil concentrations would allow these ions to be used as mobile tracers (Fuller, 2001). Over time the increase in Cl^- and SO_4^{2-}, resulting from effluent irrigation could lead to increased salt loadings of surface and groundwater.

ECe at the completion of the study were < 1.0 dS m^{-1}, which would not affect most crops like poplar, reed canarygrass, timothy, or alsike clover (Wentz 2001). ECe in this study (maximum 1.4 dS m^{-1}; Figure 6.9) was comparable to values found by Patterson et al. (2008b) but lower than those found by Shannon et al. (1999), Bañuelos et al. (1999), and Patterson et al. (2008a). Shannon et al. (1999) suggested hybrid poplar clones used in their study had a salt tolerance threshold of 5.53 (±0.67) dS m^{-1} with a 12% decrease in yield for each unit increase in salinity.

6.3.3 Synthesis and Management Implications

The forage intercrop reduced TSW40 slightly relative to that of the cultivated plots. TSW40 could possibly have been further reduced by minimizing nutrient limitations, like N + P. Fertilizer applications would also reduce chances of potential nutrient imbalances (i.e., K, Ca, and Mg) in both the soil and resulting imbalances in the irrigated forages if used for feed (e.g., tetany resulting from K and Mg imbalances in the rumen) (Grattan et al. 2004). However, increasing the fertility at the site would promote increased water use but also increase salinization rates within the root zone if effluent irrigation projects were not managed properly. As a result, a balance must be struck between crop water use and leaching requirements. Crop residue and irrigation timing, such as irrigating during periods with low evaporation (e.g., at night), would help reduce evaporative losses. Managing irrigation would increase irrigation efficiency and allow more water to be available for crop use or leaching requirements (Fipps 2003).

Decomposition of crop or other organic residues (e.g., compost, manure, and biosolids) incorporated into the soil will also help increase soil porosity and as decomposition proceeds should help solubilize Ca in the soil, which would reduce soil sodicity (Sekhon and Bajwa 1993; Mishra et al. 2004). Pulp and paper mills in addition to producing effluents also produce combined biosolids (Cabral et al. 1998; Jordan et al. 2002; N'Dayegamiye et al. 2002). These biosolids are a concentrated form of waste activated sludge (WAS) which has undergone the dewatering process leaving a product with 65-70% solids. In areas where effluent irrigation is possible, soils with low organic matter levels could be amended initially with these residuals prior to irrigation or throughout the course of a project. These biosolids can also provide a suitable source of NPKS in addition to Ca along with providing organic matter (OM) which would help improve soil physical and chemical properties. As the additional OM decomposed this would release both nutrients (N'Dayegamiye et al. 2002), and mobilize Ca^{2+} by increasing the concentration of organic acids thus, dissolving some fo the $CaCO_3$ (Sekhon and Bajwa 1993; Mishra et al. 2004), releasing Ca^{2+} into soil solution. Applications of soil amendments like gypsum, elemental S, lime, or other organic amendments, which would maintain good soil structure (i.e., aggregation, porosity, etc.) and limit increases in SAR would help improve the success of an effluent irrigation program (Howe and Wagner 1996; Bauder and Brock 2001).

Facilities like pulp or paper mills often have a capability to utilize good quality water (e.g., river water) to supplement or dilute effluents for irrigation programs. However, under a cyclic irrigation strategy this could also be accomplished through regional precipitation. Supplemental or cyclic irrigation strategies would be one option for this region as water deficits occur throughout the season primarily towards the middle and later stages of the growing season. This approach allows precipitation received early in the season and later in the fall to provide salinity control within the rooting zone while effluent applied during the growing season reduces possible water deficits that are occurring for the growing trees or agricultural crops. Similar strategies have been applied to agricultural crops like wheat (Naresh et al. 1993). In humid and sub-humid climates vapor pressure deficits, on average, will be lower than in arid regions during the growing season, increasing one aspect of the irrigation efficiency since less water is lost to evaporation.

Patterson et al. (2008b) indicated that KPME effluents could be used for irrigation provided ratios of KPME to water (or precipitation) did not exceed 50% of the seasonal water requirement. More information is needed on irrigation scheduling in the area. The region where the study soil was collected receives approximately 340 mm (~2.7 mm d^{-1}) of precipitation from May to mid-September. The growth chamber studies conducted by Patterson et al. (2008a; 2007b) applied KPME effluents and effluent dilutions at 2 to 3 times greater than the daily estimate of ~2.7 mm d^{-1}. Potential evapotranspiration rates (PET) are estimated to range from 3 to 5 mm day^{-1}, leaving a water deficit of 0.3 to 2.3 mm d^{-1} throughout the summer that could be made up through irrigation. Even when considering PET is at its peak (i.e., 5 mm d^{-1}) this would assume a daily deficit of 2.3 mm d^{-1} for the entire growing season, which is unlikely for this area. It is more likely KPME would be used for irrigation only for a few weeks during the season. At 25-50% of the estimated deficit (i.e., 2.3 mm d^{-1}) KPME would be providing up to 1.2 mm d^{-1} of supplemental water and could be applied while maintaining soil EC and SAR (Patterson et al. 2008b) within tolerable limits of many agricultural and tree crops like poplar, wheat, timothy, or alsike clover (Shannon et al. 1999; Wentz 2001).

For supplemental irrigation to be applied more effectively in this region, more information is required on the water use requirements of hybrid poplar, forages, and other agricultural crops in this region. Additionally, more research needs to be conducted on developing supplemental irrigation strategies to allow the use of poorer quality waters in these areas to reduce the reliance on better quality waters but also help improve surface water quality. Further research needs to be conducted on the irrigation requirements for various cropping systems, timing, drainage, and crop water use under sub-humid climates.

6.4 CONCLUSIONS

Kraft pulp mill effluent could be used as a water source for supplemental irrigation in sub-humid areas during times when water is limiting during the growing season. Differences in the uniformity of application resulted in increased application of dissolved salts to areas nearest the sprinklers, as would be expected. This should be taken into consideration for future studies. The accumulation of soluble salts within the rooting zone can be reduced with a combination of precipitation, better quality water, such as potable water, and possibly the addition of organic or Ca^{2+} based soil amendments. Irrigation with KPME increased soluble Na^+, SO_4^{2-}, and Cl^- in saturated paste extracts after three consecutive years of irrigation, but their concentrations decreased after two subsequent years with no irrigation. Sodium remains the primary issue that in the long term will ultimately limit the use of KPME. The use of an intercrop also resulted in a slight reduction of applied dissolved nutrients because of plant uptake. However, this was only based on soil analyses since no tissue analyses were conducted. Nutrient uptake of the intercrop should be further evaluated in future effluent management research to determine if nutrient limitations become evident, or if synergies could be established between tree crops and N-fixing forages. More research needs to be conducted on crop water requirements in this area when considering the use of KPME as a supplemental source of irrigation water, in addition to the impacts of proper nutrient management, irrigation timing, and soil variability would have in these projects.

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Table 6.1. Annual (2001-2006) and growing season climate data at the Environment Canada MET Station (Athabasca 2) for average air temperature, total precipitation, and growing degree days [base temperature (5°C)] and the Canadian Climate Normals (CCN; 1971 to 2000) data for the area

	[a] Annual			[a] Growing Season (May 1 to Sept 30)		
Year	Average Temp (°C)	Precip. (mm)	Growing Degree Days (5°C)	Average Temp (°C)	Precip. (mm)	Growing Degree Days (5°C)
2001	3.6	491	1 460	14.1	398	1 396
2002 (Yr-1)	1.6	339	1 312	13.2	210	1 296
2003 (Yr-2)	1.5	491	1 348	12.2	324	1 216
2004 (Yr-3)	2.3	571	1 239	12.4	386	1 170
2005 (Yr-4)	2.7	346	1 293	12.6	280	1 174
2006 (Yr-5)	1.9	527	1 146	11.1	411	1 110
[b] CCN	2.2	504	1 370	13.2	349	1 270

[a] Source: Athabasca 2 Station, http://climate.weatheroffice.ec.gc.ca/climateData/monthlydata_e.html?timeframe=2&Prov=XX&Station ID=2467 (Athabasca 2: 2002-2006)

[b] Canadian Climate Normals (CCN; 1971-2000) http://www.climate.weatheroffice.ec.gc.ca/climate_normals (Athabasca 2)

Table 6.2. Average selected chemical and physical characteristics of the study soil (n=8), water (n=8) and Kraft pulp mill effluent (n=8; KPME) used in the field study. Samples were collected in 2002.

Characteristic	Soil					[a]Kraft Pulp Mill Effluent (KPME)	Irrig. Water
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm		
Bulk Density (Mg m^{-3})	1.34	1.43	1.45	1.41	1.31		
[b] PAW, (cm^3 cm^{-3} x100)	15.8	21.1	18.5	20.1	21.3		
Texture							
Sand (g kg^{-1})	51.2	61.9	68.5	66.9	65.0		
Silt (g kg^{-1})	34.1	22.6	16.2	15.7	14.9		
Clay (g kg^{-1})	14.7	15.5	15.4	17.4	20.1		
pH	5.9	5.8	5.9	6.1	6.3	8.3	8.0
[c] ECe; ECw (dS m^{-1})	0.8	0.5	0.4	0.3	0.3	2.0	0.3
Saturation (%)	37.3	33.1	32.6	35.1	35.7		
[d] TDS (mg L^{-1})						1.4	0.2
HCO_3 (mg L^{-1})						330.0	87.1
CO_3 (mg L^{-1})						7.3	5.0
[e] SAR	0.3	0.4	0.5	0.5	0.5	8.3	0.6
[f] SAR_{adj}						11.0	0.5
Ca (mg L^{-1})	109.0	60.6	46.9	34.0	30.5	109.7	26.7
K (mg L^{-1})	4.3	2.6	2.1	2.2	1.9	38.5	2.4
Mg (mg L^{-1})	15.1	10.8	11.2	9.3	8.3	15.1	10.2
Na (mg L^{-1})	13.1	12.1	11.8	11.9	11.7	334.6	12.4
Cl (mg L^{-1})	9.5	10.1	9.7	7.9	7.7	139.9	2.5
SO_4 (mg L^{-1})	35.5	27.1	47.3	23.2	19.7	593.0	59.0

[a] KPME – Kraft Pulp Mill Effluent

[b] PAW – Plant Available Water: Pressure level chosen for the loam textured Eluviated Dystric Brunisol soil was 1500 kPa for all increments to estimate wilting point, while field capacity estimates were made at 33 kPa (0-20 cm) and 10 kPa (20-40, 40-60, 60-80, and 80-100 cm) and, respectively.

[c] ECe – Electrical Conductivity of saturated paste extracts for soils; ECw – Electrical Conductivity of irrigation source

[d] TDS – Total Dissolved Solids

[e] SAR – Sodium Adsorption Ratio

[f] SAR_{adj} – Adjusted Sodium Adsorption Ratio (Ayers and Westcot 1994)

Table 6.3. P values for pH, ECe, sodium adsorption ratio (SAR), and soluble Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, and SO_4^{2-} measured in the saturated paste extracts for the 0-20 cm depth increment

Effect	pH	[a]ECe	SAR	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}
[b]Treatment (T)	0.055	< 0.001	< 0.001	0.006	< 0.001	0.019	0.051	< 0.001	< 0.001
[c]Vegetation (V)	0.767	0.038	0.724	0.014	0.103	0.814	0.225	0.404	0.158
T x V	0.081	0.980	0.110	0.401	0.530	0.094	0.237	0.130	0.748
[d]Uniformity (U)	0.860	0.012	0.006	0.216	0.009	0.076	0.027	0.001	0.080
T x U	0.964	0.020	0.006	0.440	0.019	0.040	0.313	0.002	0.108
U x V	0.875	0.836	0.049	0.710	0.644	0.407	0.161	0.540	0.909
T x U x V	0.913	0.484	0.072	0.541	0.305	0.179	0.083	0.575	0.963
Year (Y)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.347	0.012	0.004	< 0.001
Y x T	0.948	< 0.001	< 0.001	< 0.001	< 0.001	0.022	< 0.001	< 0.001	< 0.001
Y x U	0.882	0.020	0.931	0.300	0.021	0.560	0.084	0.097	0.034
Y x T x U	0.881	0.085	0.929	0.197	0.027	0.855	0.219	0.002	0.024
Y x V	0.450	0.069	0.905	0.077	0.927	0.046	0.407	0.366	0.670
Y x T x V	0.997	0.976	0.936	0.974	0.778	0.199	0.942	0.422	0.954
Y x U x V	0.627	0.960	0.929	0.928	0.977	0.478	0.719	0.902	1.000
Y x T x U x V	0.967	0.931	0.999	0.850	0.682	0.288	0.756	0.965	1.000

[a] ECe – Electrical Conductivity of saturated paste extracts for soils

[b] Treatments = Kraft pulp mill effluent (KPME), Irrigation water, non-irrigated control

[c] Vegetation = Type of vegetation coverage either hybrid poplar only or hybrid poplar plus forage mixture

[d] Uniformity = based on rate of application, two areas identified as high and low

Table 6.4. P values for pH, ECe, sodium adsorption ratio (SAR), and soluble Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, and SO_4^{2-} measured in the saturated paste extracts for the 20-40 cm depth increment

Effect	pH	[a]ECe	SAR	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}
[b]Treatment (T)	0.140	< 0.001	0.006	< 0.001	< 0.001	0.002	< 0.001	0.001	< 0.001
[c]Vegetation (V)	0.279	< 0.001	0.151	0.017	0.526	0.053	0.024	0.766	0.109
T x V	0.292	0.221	0.680	0.599	0.985	0.278	0.187	0.583	0.315
[d]Uniformity (U)	0.449	0.003	0.025	0.088	0.003	0.599	0.288	< 0.001	0.016
T x U	0.665	0.004	0.047	0.127	0.002	0.457	0.814	0.001	0.027
U x V	0.643	0.087	0.192	0.281	0.218	0.680	0.414	0.323	0.459
T x U x V	0.729	0.375	0.574	0.379	0.459	0.113	0.774	0.883	0.824
Year (Y)	< 0.001	0.160	< 0.001	0.001	0.782	< 0.001	0.019	< 0.001	0.189
Y x T	0.793	0.005	< 0.001	0.024	< 0.001	0.022	0.135	< 0.001	0.009
Y x U	0.665	0.345	0.266	0.207	0.225	0.878	0.155	0.353	0.149
Y x T x U	0.247	0.053	0.712	0.015	0.019	0.479	0.043	0.069	0.014
Y x V	0.458	0.637	0.084	0.541	0.991	0.382	0.730	0.617	0.541
Y x T x V	0.985	0.970	0.680	0.887	0.999	0.868	0.981	0.910	0.839
Y x U x V	0.500	0.912	0.417	0.638	0.954	0.008	0.782	0.615	0.522
Y x T x U x V	0.887	0.971	0.931	0.981	0.964	0.081	0.863	0.972	0.687

[a] ECe – Electrical Conductivity of saturated paste extracts for soils
[b] Treatments = Kraft pulp mill effluent (KPME), Irrigation water, non-irrigated control
[c] Vegetation = Type of vegetation coverage either hybrid poplar only or hybrid poplar plus forage mixture
[d] Uniformity = based on rate of application, two areas identified as high and low

Table 6.5. P values for pH, ECe, sodium adsorption ratio (SAR), and soluble Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, and SO_4^{2-} measured in the saturated paste extracts for the 40-60 cm depth increment

Effect	pH	[a]ECe	SAR	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}
[b]Treatment (T)	0.140	< 0.001	0.344	0.005	0.003	0.021	0.008	0.021	< 0.001
[c]Vegetation (V)	0.144	0.001	0.018	0.002	0.062	0.004	0.004	0.483	0.030
T x V	0.270	0.875	0.984	0.580	0.908	0.471	0.975	0.929	0.016
[d]Uniformity (U)	0.348	0.020	0.089	0.195	0.004	0.528	0.094	0.001	0.008
T x U	0.813	0.009	0.078	0.360	0.007	0.293	0.538	0.005	0.037
U x V	0.792	0.679	0.887	0.328	0.123	0.156	0.270	0.389	0.613
T x U x V	0.487	0.382	0.804	0.513	0.723	0.848	0.736	0.756	0.951
Year (Y)	< 0.001	< 0.001	< 0.001	0.953	< 0.001	0.066	0.007	< 0.001	< 0.001
Y x T	0.826	< 0.001	< 0.001	< 0.001	< 0.001	0.582	< 0.001	< 0.001	< 0.001
Y x U	0.739	0.076	0.432	0.260	0.513	0.270	0.155	0.050	0.516
Y x T x U	0.170	0.057	0.232	0.030	0.063	0.193	0.018	0.337	0.008
Y x V	0.911	0.103	0.183	0.647	0.774	0.382	0.736	0.246	0.961
Y x T x V	0.987	0.798	0.067	0.126	0.744	0.300	0.072	0.910	0.964
Y x U x V	0.873	0.678	0.971	0.979	0.729	0.956	0.911	0.986	0.935
Y x T x U x V	0.969	0.928	0.230	0.951	0.982	0.135	0.632	0.923	0.988

[a] ECe – Electrical Conductivity of saturated paste extracts for soils

[b] Treatments = Kraft pulp mill effluent (KPME), Irrigation water, non-irrigated control

[c] Vegetation = Type of vegetation coverage either hybrid poplar only or hybrid poplar plus forage mixture

[d] Uniformity = based on rate of application, two areas identified as high and low

Table 6.6. P values for pH, ECe, sodium adsorption ratio (SAR), and soluble Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, and SO_4^{2-} measured in the saturated paste extracts for the 60-80 cm depth increment

Effect	pH	[a] ECe	SAR	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}
[b] Treatment (T)	0.086	< 0.001	0.161	0.001	0.001	0.001	0.002	0.012	< 0.001
[c] Vegetation (V)	0.132	0.003	0.002	0.023	0.497	0.450	0.079	0.586	0.660
T x V	0.091	0.593	0.158	0.445	0.876	0.371	0.480	0.851	0.726
[d] Uniformity (U)	0.068	0.459	0.010	0.210	0.020	0.554	0.003	0.001	0.018
T x U	0.362	0.006	0.026	< 0.001	0.004	0.224	< 0.001	0.001	0.002
U x V	0.934	0.955	0.793	0.933	0.345	0.600	0.750	0.690	0.995
T x U x V	0.339	0.003	0.396	0.255	0.998	0.445	0.840	0.386	0.297
Year (Y)	< 0.001	< 0.001	< 0.001	0.006	< 0.001	0.009	< 0.001	< 0.001	< 0.001
Y x T	0.754	< 0.001	0.028	0.001	< 0.001	0.239	0.001	0.111	< 0.001
Y x U	0.817	0.699	0.352	0.896	0.143	0.363	0.566	0.045	0.671
Y x T x U	0.810	0.078	0.033	0.428	0.030	0.976	0.017	0.264	0.435
Y x V	0.577	0.054	0.441	0.186	0.049	0.870	0.631	0.684	0.665
Y x T x V	0.921	0.183	0.006	0.199	0.512	0.677	0.017	0.892	0.864
Y x U x V	0.815	0.927	0.807	0.662	0.937	0.462	0.053	0.993	0.601
Y x T x U x V	0.992	0.211	0.177	0.502	0.152	0.664	0.221	0.590	0.558

[a] ECe – Electrical Conductivity of saturated paste extracts for soils

[b] Treatments = Kraft pulp mill effluent (KPME), Irrigation water, non-irrigated control

[c] Vegetation = Type of vegetation coverage either hybrid poplar only or hybrid poplar plus forage mixture

[d] Uniformity = based on rate of application, two areas identified as high and low

Table 6.7. P values for pH, ECe, sodium adsorption ratio (SAR), and soluble Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, and SO_4^{2-} measured in the saturated paste extracts for the 80-100 cm depth increment

Effect	pH	[a] ECe	SAR	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}
[b] Treatment (T)	0.155	< 0.001	0.010	0.005	< 0.001	0.003	0.002	0.080	0.002
[c] Vegetation (V)	0.017	0.001	0.001	0.006	0.996	0.457	0.058	0.516	0.501
T x V	0.265	0.306	0.368	0.156	0.476	0.073	0.421	0.547	0.269
[d] Uniformity (U)	0.029	0.034	0.114	0.038	0.002	0.010	0.003	< 0.001	0.006
T x U	0.022	0.002	0.722	0.007	0.001	0.019	0.001	0.032	0.008
U x V	0.209	0.278	0.426	0.521	0.818	0.363	0.502	0.394	0.860
T x U x V	0.401	0.400	0.653	0.834	0.745	0.309	0.959	0.433	0.765
Year (Y)	< 0.001	< 0.001	< 0.001	0.001	< 0.001	0.003	0.001	< 0.001	< 0.001
Y x T	0.772	< 0.001	0.010	< 0.001	< 0.001	0.720	< 0.001	0.919	< 0.001
Y x U	0.986	0.628	0.855	0.251	0.929	0.751	0.393	0.444	0.512
Y x T x U	0.966	0.507	0.930	0.175	0.872	0.978	0.402	0.967	0.077
Y x V	0.604	0.040	0.657	0.485	0.340	0.795	0.896	0.828	0.753
Y x T x V	0.964	0.564	0.095	0.210	0.251	0.583	0.406	0.445	0.775
Y x U x V	0.973	0.661	0.540	0.859	0.940	0.941	0.360	0.686	0.900
Y x T x U x V	0.946	0.766	0.999	0.858	0.819	0.980	0.632	0.907	0.973

[a] ECe – Electrical Conductivity of saturated paste extracts for soils

[b] Treatments = Kraft pulp mill effluent (KPME), Irrigation water, non-irrigated control

[c] Vegetation = Type of vegetation coverage either hybrid poplar only or hybrid poplar plus forage mixture

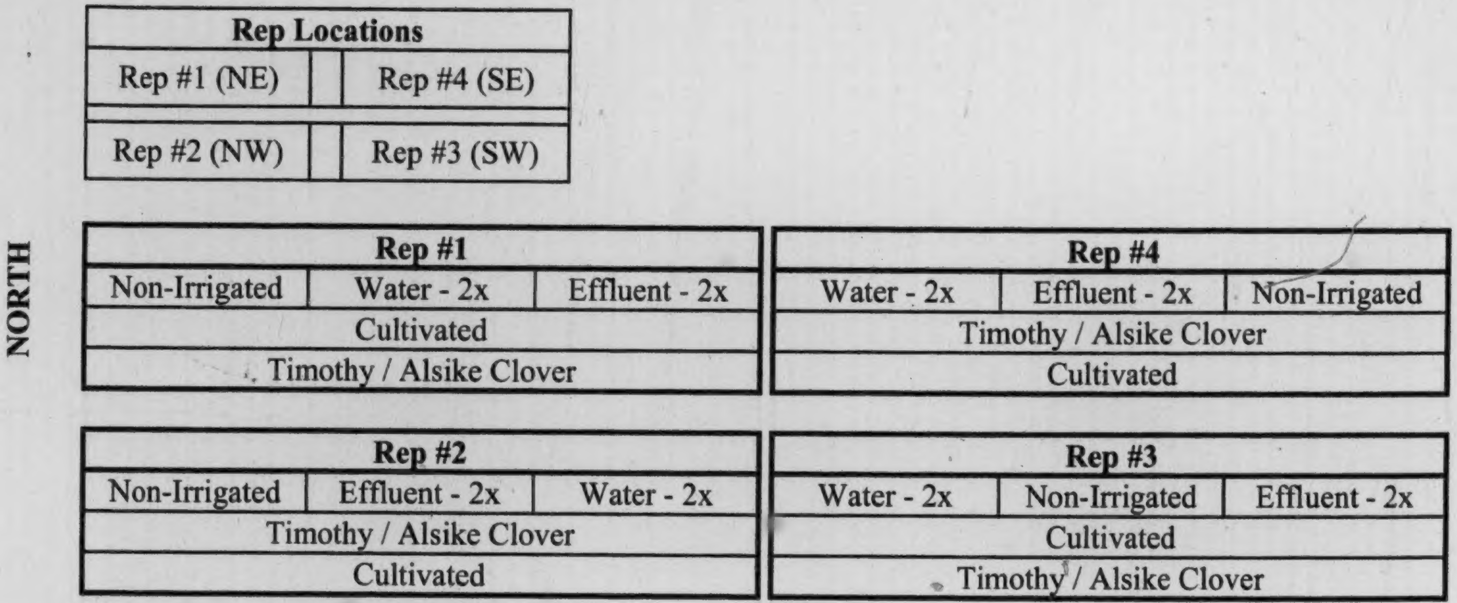
[d] Uniformity = based on rate of application, two areas identified as high and low

Table 6.8. $LSD_{0.05}$ values for treatment mean separations for Figure 6.6 to Figure 6.9 for each year according to each depth sampled and analyzed for sodium adsorption ratio (SAR), and soluble Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, and ECe measured in saturated paste extracts

			---------------------- mg kg^{-1}	----------------------					dS cm^{-1}
Year	Depth	[a] SAR	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	SO_4^{2-}	[b] ECe
Yr-2: 2003	0-20 cm	0.80	8.9	8.4	1.4	0.54	6.7	23.5	0.15
	20-40 cm	0.91	6.5	5.9	1.5	0.28	3.8	18.3	0.13
	40-60 cm	0.67	4.5	5.9	1.6	0.57	3.5	16.3	0.10
	60-80 cm	0.34	3.4	6.4	2.0	0.64	3.9	16.3	0.11
	80-100 cm	0.36	4.2	8.4	2.5	0.79	6.4	21.1	0.10
Yr-3: 2004	0-20 cm	0.80	8.9	8.4	1.4	0.54	6.7	23.5	0.15
	20-40 cm	0.91	6.5	5.9	1.5	0.28	3.8	18.3	0.13
	40-60 cm	0.67	4.5	5.9	1.7	0.57	3.5	16.3	0.10
	60-80 cm	0.34	3.4	6.5	2.0	0.64	3.9	16.3	0.12
	80-100 cm	0.36	4.3	8.5	2.5	0.79	6.4	21.2	0.10
Yr-4: 2005	0-20 cm	0.81	9.0	8.4	1.4	0.54	6.7	23.4	0.15
	20-40 cm	0.93	6.6	5.9	1.5	0.28	3.8	18.3	0.13
	40-60 cm	0.68	4.6	5.9	1.7	0.57	3.6	16.4	0.10
	60-80 cm	0.34	3.5	6.5	2.0	0.64	3.9	16.3	0.12
	80-100 cm	0.36	4.3	8.6	2.5	0.78	6.4	21.3	0.10
Yr-5: 2006	0-20 cm	0.89	10.0	8.3	1.4	0.54	6.9	23.1	0.15
	20-40 cm	1.05	7.5	5.7	1.5	0.29	3.8	18.0	0.13
	40-60 cm	0.77	5.5	6.5	1.9	0.57	4.0	17.0	0.11
	60-80 cm	0.35	3.7	6.9	2.2	0.62	4.2	16.3	0.12
	80-100 cm	0.36	4.7	9.8	2.8	0.77	6.6	22.6	0.10

[a] SAR - Sodium Adsorption Ratio

[b] ECe - Electrical Conductivity of saturated paste extracts



Rep Locations	
Rep #1 (NE)	Rep #4 (SE)
Rep #2 (NW)	Rep #3 (SW)

Rep #1		
Non-Irrigated	Water - 2x	Effluent - 2x
Cultivated		
Timothy / Alsike Clover		

Rep #4		
Water - 2x	Effluent - 2x	Non-Irrigated
Timothy / Alsike Clover		
Cultivated		

Rep #2		
Non-Irrigated	Effluent - 2x	Water - 2x
Timothy / Alsike Clover		
Cultivated		

Rep #3		
Water - 2x	Non-Irrigated	Effluent - 2x
Cultivated		
Timothy / Alsike Clover		

Figure 6.1. Study site layout including location of irrigation and vegetation treatments, see Figure 6.2 for explanation of example of the layout within each replication.

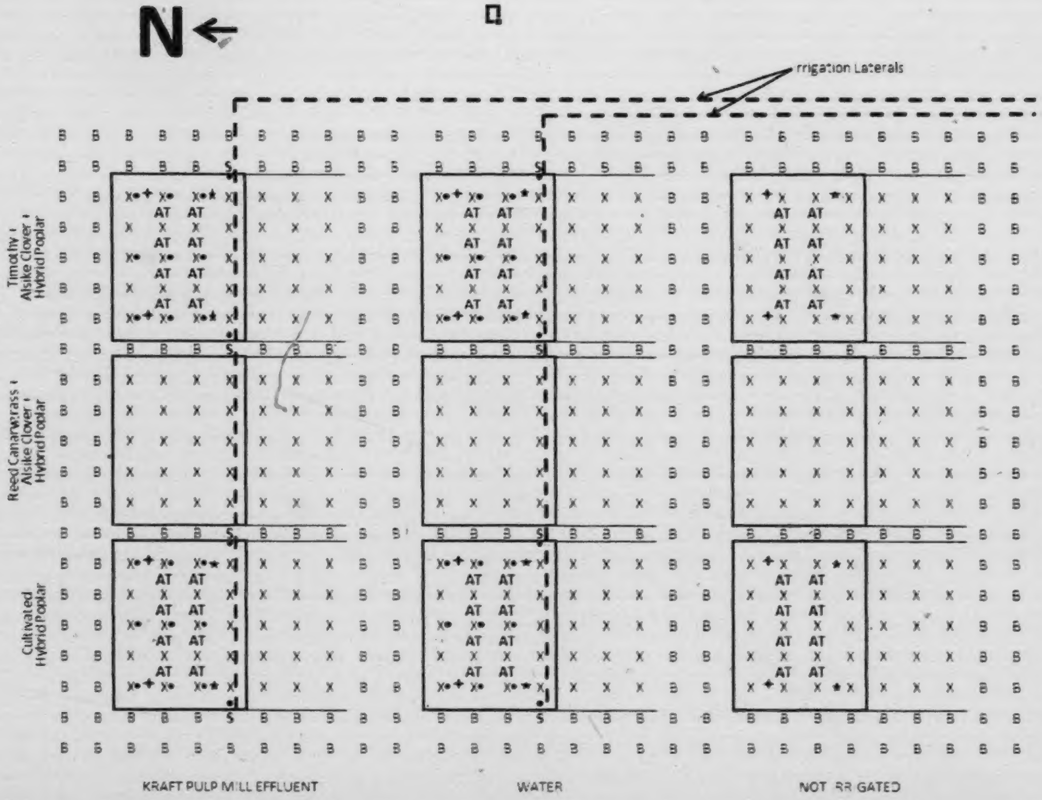

N
Irrigation Laterals
Timothy + Alsike Clover + Hybrid Poplar
Reed Canarygrass + Alsike Clover + Hybrid Poplar
Cultivated Hybrid Poplar
KRAFT PULP MILL EFFLUENT
WATER
NOT IRRIGATED

Figure 6.2. Layout of one of the four replications (Figure 6.1) used in the field study; treatment areas were planted with Walker poplar (X) and surrounded by two buffer rows (B) around the edge of each irrigation treatment with one row of buffer trees between each of the vegetation treatments. Also shown are the locations where catch cans (•) were located to determine application uniformity, the locations of the access tubes (AT) used for soil moisture measurements, and soil sample locations from areas of high application (★) and low application (✦). Only data from the areas planted with timothy, alsike clover, and hybrid poplar and hybrid poplar cultivated between tree rows are discussed in this paper. Locations of the four sprinkler nozzles (S) are indicated along with the location of the laterals, shown by the black dashed lines, which supplied the effluent or water from the storage tanks.

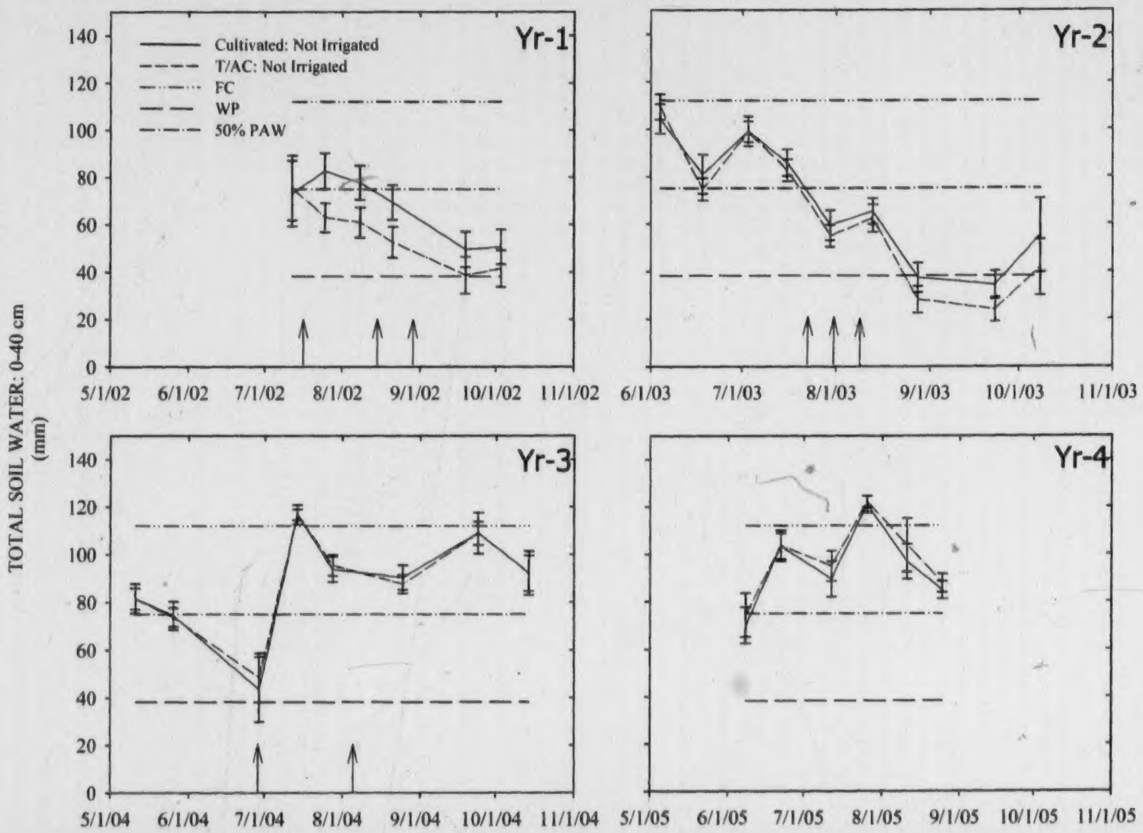


Figure 6.3. Total soil water (TSW40; mm) of the upper 40 cm of the soil profile in plots in which no irrigation occurred and were planted with hybrid poplar. Plots were either kept cultivated between tree rows or intercropped with timothy and alsike clover (T/AC). Arrows show dates on which irrigation events occurred in plots irrigated with either water or KPME (Yr-1 = 2002).

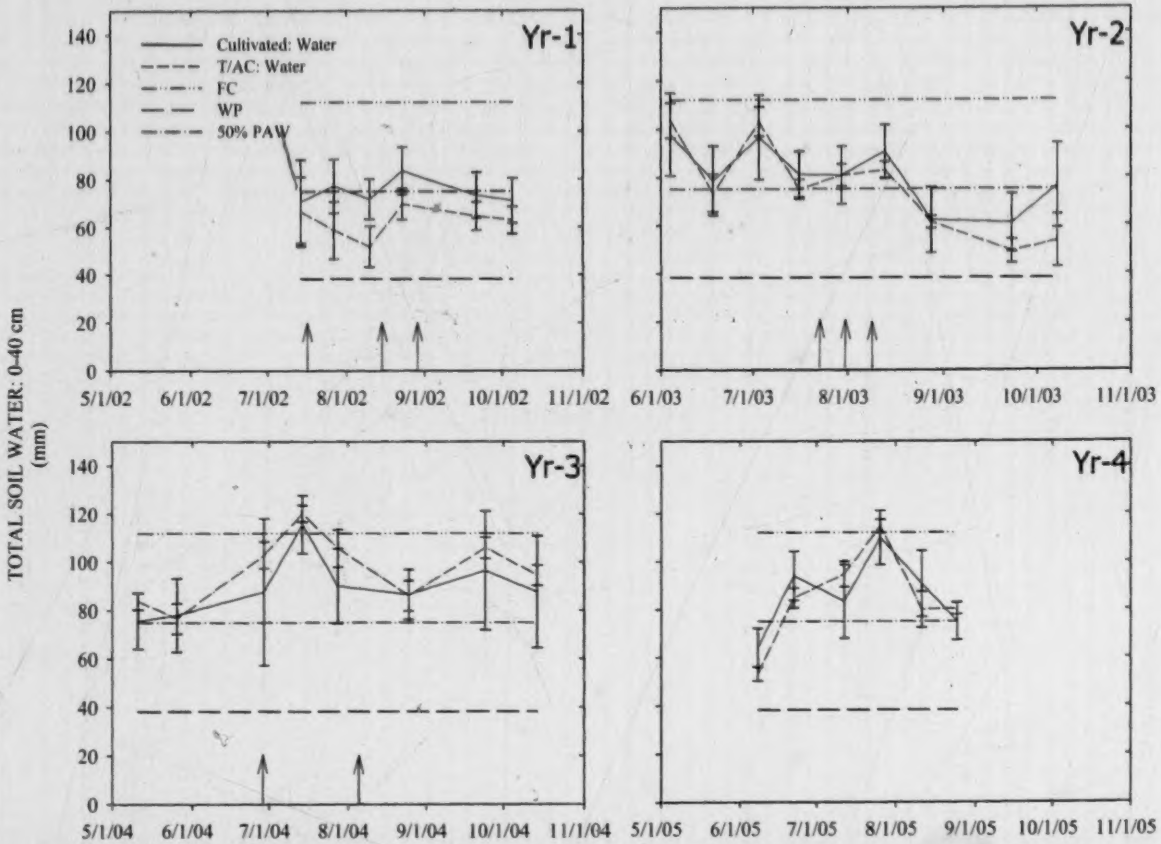


Figure 6.4. Total soil water (TSW40; mm) of the upper 40 cm of the soil profile in plots irrigated with water and planted with hybrid poplar. Plots were either kept cultivated between tree rows or intercropped with timothy and alsike clover (T/AC). Arrows show dates on which irrigation events occurred (Yr-1 = 2002).

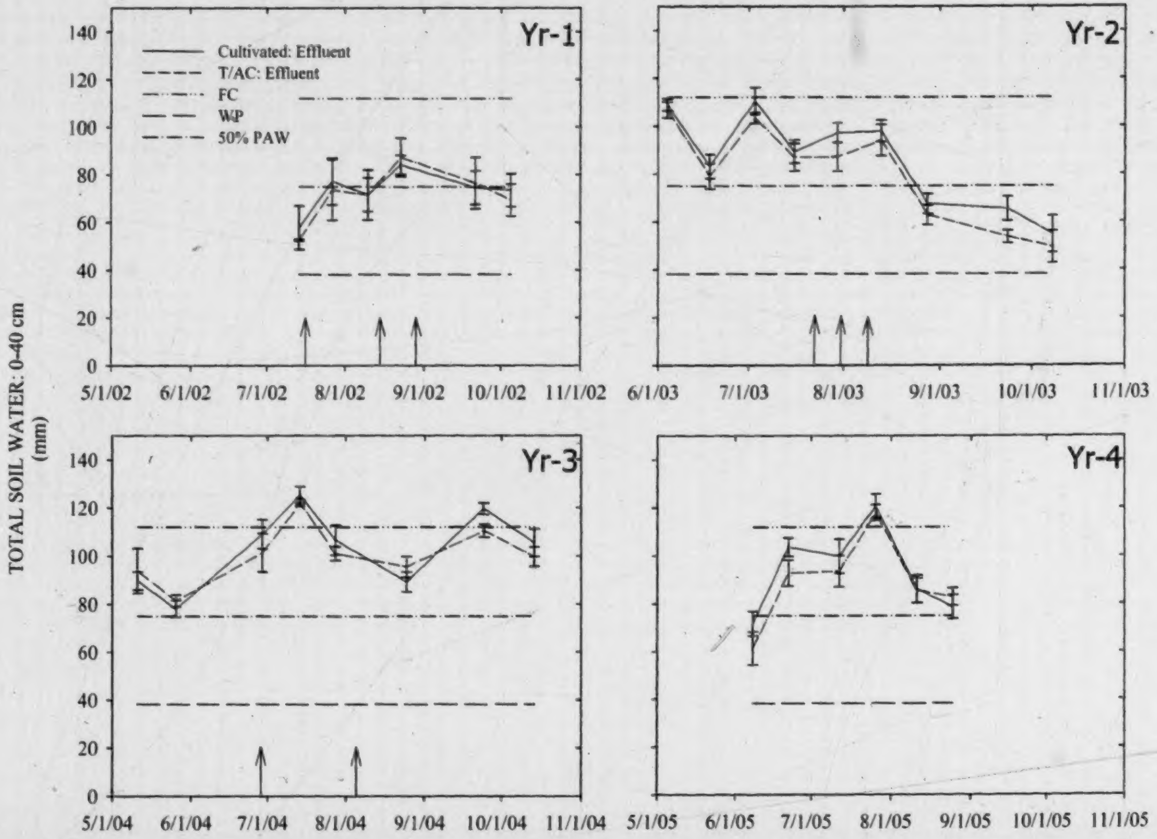


Figure 6.5. Total soil water (TSW40; mm) of the upper 40 cm of the soil profile in plots irrigated with KPME and planted with hybrid poplar. Plots were either kept cultivated between tree rows or intercropped with timothy and alsike clover (T/AC). Arrows show dates on which irrigation occurred (Yr-1 = 2002).

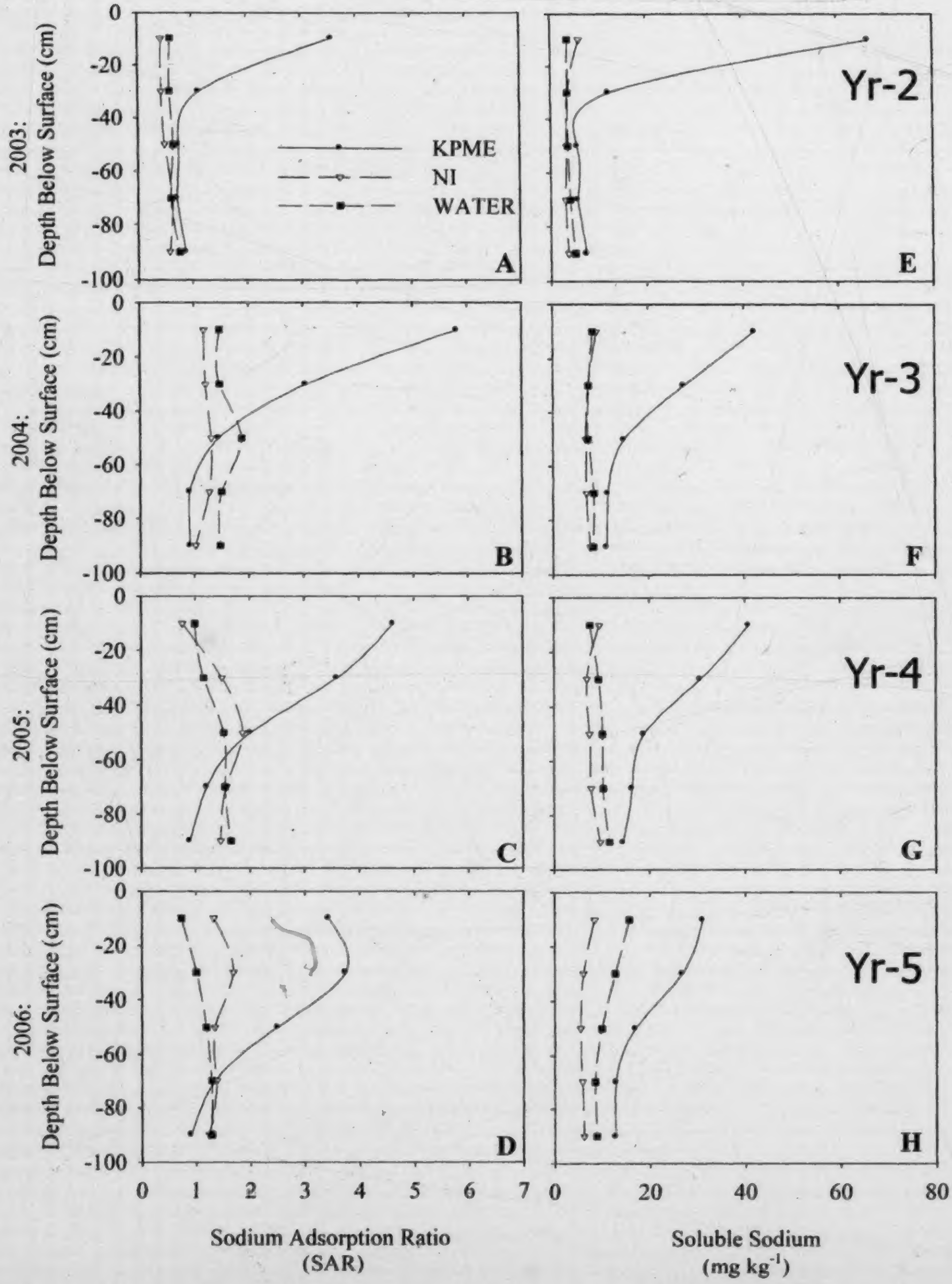


Figure 6.6. Average sodium adsorption ratio (SAR) (A-D) and soluble Na (E-H) in saturated paste extracts of non-irrigated (NI) soils and soils irrigated with water or Kraft pulp mill effluent (KPME) after three years of irrigation from 2002 to 2004 followed by two years with no irrigation 2005 to 2006. Soil samples were collected in October of each year.

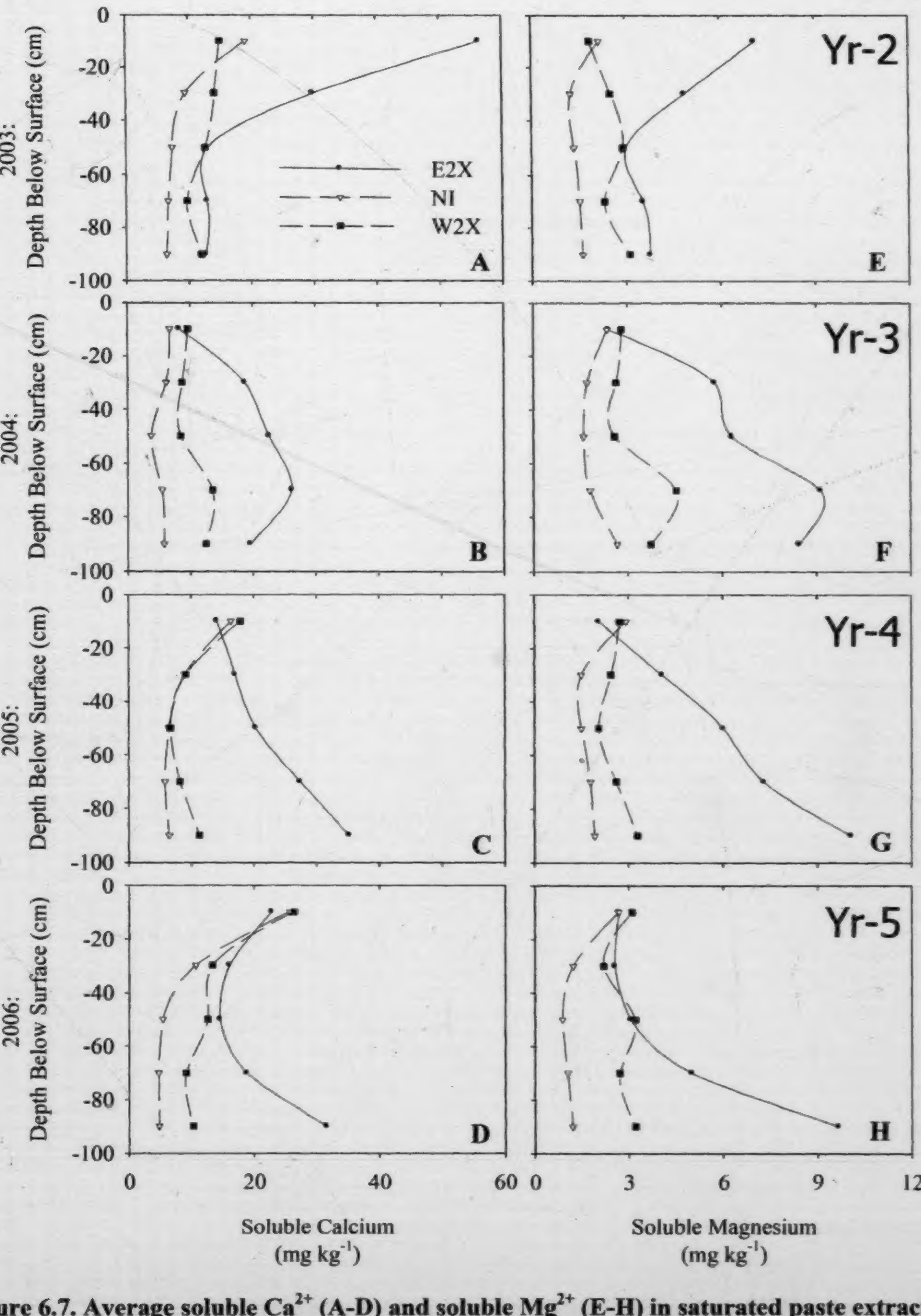


Figure 6.7. Average soluble Ca^{2+} (A-D) and soluble Mg^{2+} (E-H) in saturated paste extracts of non-irrigated (NI) soils and soils irrigated with water or Kraft pulp mill effluent (KPME) after three years of irrigation from 2002 to 2004 followed by two years with no irrigation 2005 to 2006. Soil samples were collected in October of each year.

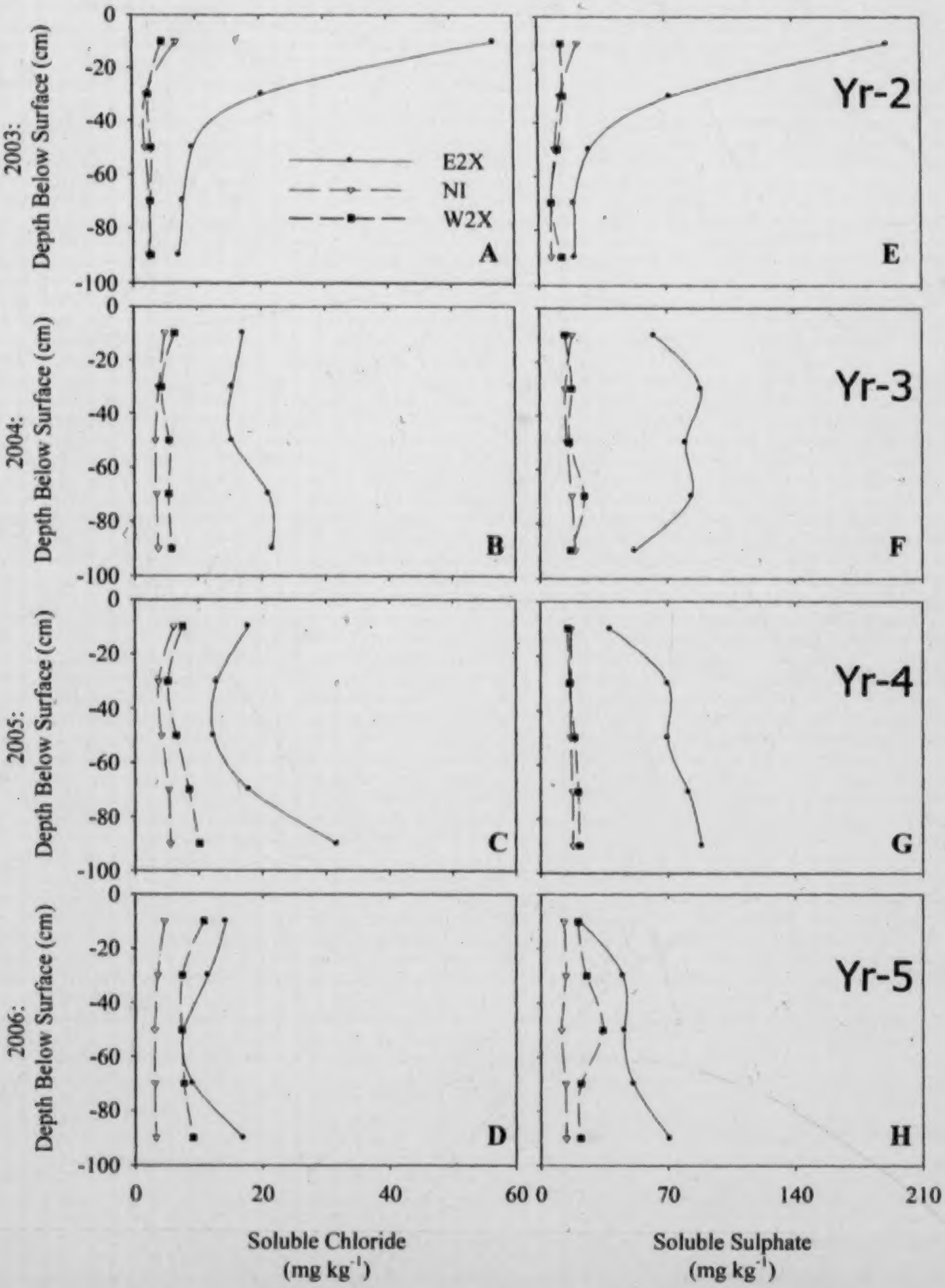


Figure 6.8. Average soluble Cl^- (A-D) and soluble SO_4^{2-} (E-H) in saturated paste extracts of non-irrigated (NI) soils and soils irrigated with water or Kraft pulp mill effluent (KPME) after three years of irrigation from 2002 to 2004 followed by two years with no irrigation 2005 to 2006. Soil samples were collected in October of each year.

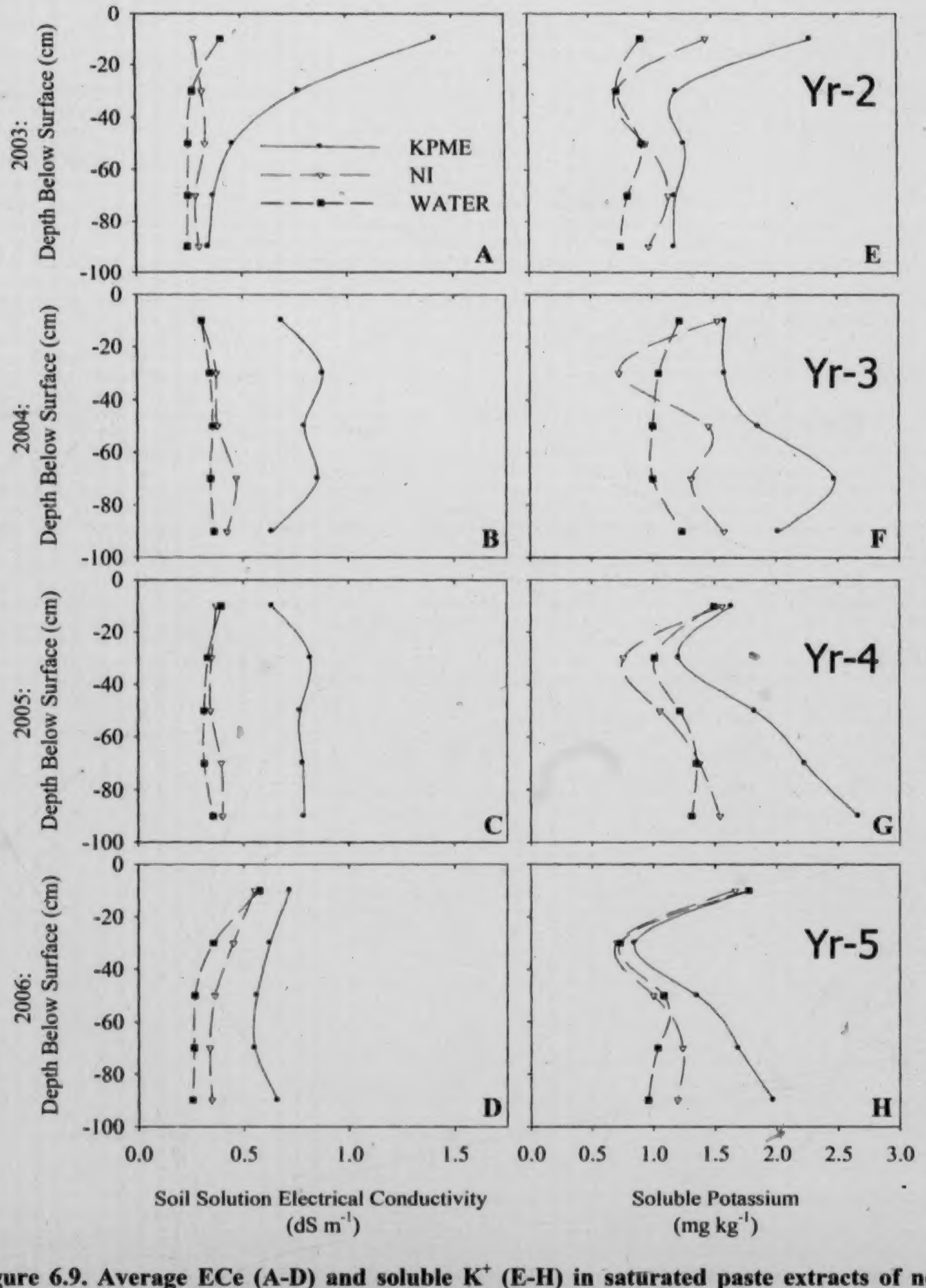


Figure 6.9. Average ECe (A-D) and soluble K^+ (E-H) in saturated paste extracts of non-irrigated (NI) soils and soils irrigated with water and Kraft pulp mill effluent (KPME) after three years of irrigation from 2002 to 2004 followed by two years with no irrigation 2005 to 2006. Soil samples were collected in October of each year.

7. *SYNTHESIS*

Irrigation has been practiced over thousands of years; from as far back as 5000-6000 BC when ancient Egyptians and Mesopotamians flood irrigated land adjacent to rivers to increase agricultural productivity in arid regions (Hillel 1998). While irrigation methods have remained consistent, technology has allowed water to be diverted further, stored in greater amounts, and applied with better control over precision and timing.

Irrigation technology has continued to develop to meet the needs of the agricultural industry. At the same time, the industry continues to face increasing competition, for the same sources of water, with other industries and municipalities. Agriculture, municipalities, and industry all need to address the issues of water quality and water quantity (Bouwer 1994; Pereira et al. 2002). Nearly 10 000 km^2 of irrigated cropland exist in Canada, 60% of which is located in Alberta (Environment Canada 2004). Like many countries, the majority of consumptive water use in Alberta is directed towards irrigation (~71%) and agriculture (~2%; livestock watering), followed by commercial/industrial and municipal uses at 14.8% and 5.4%, respectively (Asano 1987; Alberta Government 2002). Primary consumption of Alberta's extracted groundwater is for commercial/industrial uses (52.8%), followed by agricultural at 25.1%, and municipal at 18.3%. Less than 0.6% of the groundwater consumed in Alberta is allocated for irrigation. Ongoing pressures to maintain water quality and preserve potable sources of water will continue to place greater strain on an irreplaceable finite resource.

Requirements for potable water and traditional methods of effluent disposal often affect the same body of water (i.e., river, lake, etc.). For example, municipalities and industries may discharge wastewater from the same source from which potable water is drawn. While they may not directly use the same water body, there can be connections through subsurface flow, or through secondary or tertiary watercourses. As the public becomes more aware of where their water comes from, and how resulting effluent streams are disposed of, the concerns over water quality are growing. Increased loadings of water bodies with nutrient rich (i.e., N and P) effluents can lead to surface or groundwater contamination and, over time, eutrophication. Discharge of effluents containing high concentrations of dissolved nutrients and salts and can lead to reductions in water quality. Industrial effluents are often discharged into water bodies, but alternatives to such disposal are actively being sought.

In recent years, there has been a trend towards the reuse of low quality water to supplement potable water sources. These sources include drainage water and effluents; their use has benefits and drawbacks. Although general irrigation principles are universal, each irrigated site provides unique physiographic, pedological, climatic, and vegetative challenges of local soils. Decisions on timing and rate of application during irrigation events appear to be simple, but many factors are involved. Effluent streams can provide valuable sources of supplemental water and nutrients, but they also pose environmental problems in water, like eutrophication, or like salinity and sodicity in soils if not properly managed (Hillel 1998). Effluent management programs need to consider long-term implications along with the short-term gains. These decisions are especially crucial as over-irrigation can raise the local water table and potentially lead to nutrient/salt accumulation in groundwater.

The term value-added has many applications and can often be applied to waste products like manures from agriculture, biosolids from municipalities, and to effluents. Since effluents are quite variable in their chemical composition, their potential impacts can vary dramatically. The most obvious advantage is their use to supplement potable sources for irrigation. However, it is not just a question of quantity but also one of quality. For example, nutrient rich effluents will be managed differently on clay textured soils than they would on sand textured fields. The management strategy under the former scenario would be much different for using saline or sodic drainage waters that can also be used for irrigation. In each case irrigation management, crop selection, and environmental factors will play important roles in the long-term success of any irrigation project (Shalhevet 1994). While drainage and effluent waters may be readily available for use as an irrigation source, their quality can place limitations on the extent and duration of their use. Of primary concern are nutrients, trace elements, and salts; all of which pose various environmental concerns that can over time limit the degree to which these waters can be used for irrigation. Salts especially pose a large problem as they can have long lasting impacts on soil physical properties in addition to affecting crop productivity if they are not managed properly (Howe and Wagner 1999).

The reliance on marginal quality waters to provide water for irrigation has continually grown, primarily in arid and semi arid regions where continuing research into the social, economic, and environmental implications plays an integral part of this expansion (Pereira et al. 2002; Qadir et al. 2003, Fuchs 2007). Increased competition and water shortages have placed efforts on finding alternative irrigation sources or alternatively, reducing irrigation rates. There has been considerable work done on municipal effluents and agricultural effluents such as liquid manures for irrigation projects. In some countries, like Israel, irrigation research has increased the use of treated effluents and marginal waters as sources of irrigation water (Qadir et al. 2003, Fuchs 2007). Fuchs (2007) stated from the early 1990s to 2005 Israel experienced a 10-fold increase in the number of research projects evaluating effluent irrigation alternatives, with projects viewed as investments with end results being financial savings and not costs. Projects have included feasibility studies, small research trials, and smaller growth chamber studies that have addressed water use, nutrient loadings, impacts on soil physical properties, and impacts to groundwater (Fuchs 2007). These studies indicated that utilization of effluents requires careful management especially in areas of high water deficits. Management decisions should be applied to avoid the build-up of salts within the root zone, manage nutrient loadings for plant uptake, but also to avoid potential surface and groundwater issues related to eutrophication and contamination. The build-up of salts may be tolerated provided the threshold concentration in the soils and irrigation water are not exceeded.

While much focus has been placed on municipal and agricultural effluents, other industries utilize and discharge vast amounts of effluents that could also be utilized for irrigation programs. Pulp and paper mills require substantial volumes of water for the projection process and discharge large volumes of effluent. Depending on the treatment process, effluents can contain nutrients, trace elements, and dissolved salts. Kraft pulp mill effluents (KPME) are comparable to municipal effluents (ME) in many ways: both contain varying concentrations of dissolved nutrients, dissolved salts, and trace elements depending on the level of treatment. The difference between the two effluent sources has more to do with salts than nutrients.

The Kraft pulping process relies on Na and SO_4 compounds during the digestion of hard and softwood chips into pulp which then undergoes bleaching, typically with Cl compounds like chlorine dioxide (ClO_2) (Smook 1989). Treatment of municipal effluents can involve Cl during disinfection. However, unlike nutrients, salts in the soil can become more problematic as they are not required in large amounts by plants, and adversely affect plant-soil water relations; creating drought-like conditions even through adequate water may be provided. Solutes like Na^+, Cl^-, and SO_4^{2-} applied though effluent applications can accumulate within the soil profile if evapotranspiration rates exceed the amount of water provided through irrigation and regional precipitation. Plants can tolerate varying degrees of salinity but if salts are allowed to accumulate and not managed, even the most tolerant plants will have reduced productivity. Unfortunately, halophytic plants generally do not have a high enough economic value to justify irrigation, while the higher value crops tend to only have low to moderate tolerances to salinity or sodicity.

Salinity and sodicity management become essential for any irrigation program involving effluents. Salinity management can involve the use of precipitation and over irrigation to leach ions like Na^+, Cl^-, and SO_4^{2-} out of the rooting zone. Excessive Na^+, adsorbed on the exchange complex in the soil, requires alternative management strategies, like applications of elemental S, or Ca and Mg based products like lime or gypsum. Applications of elemental S can create zones of acidity to solubilize calcium present in the soil, while gypsum and lime can provide soluble Ca^{2+} and Mg^{2+}, which can displace the adsorbed Na^+, allowing it to be leached out of the root zone. Cropping systems, like agroforestry, have the potential to renovate municipal and industrial effluents at more northern latitudes but research into incorporating effluents as supplemental sources of irrigation water has been limited there. Water limitations in these regions can be sporadic throughout the season, and may vary from year to year, not justifying the high costs associated with irrigation programs. However, effluent irrigation projects can be integrated into projects addressing issues of nutrient management, crop production, carbon sequestration, and water quality.

7.1 EFFLUENT ALTERNATIVES

Effluents are categorized based on one of three levels of treatment, the most basic being primary treatment to more complex tertiary treatment systems. For many municipal and industrial effluent treatment systems, primary and secondary levels of treatment are quite common. These systems can be used independently of one another or in combination. Primary treatment removes grit and floating material that can be easily removed. Secondary treatment allows for further degradation of the biological components, like human and food wastes, from the effluent. This treatment includes options such as filtration, aeration, and activated sludge systems that incorporate nutrients and biological organisms for the removal of organic compounds. Tertiary treatment is a further stage for improving effluent quality and can include filtration, lagoons, constructed wetlands, and nutrient removal, primarily nitrogen and phosphorus.

The municipal effluent used in this study was treated through a set of aerated lagoons. The Kraft pulp mill effluents go through an activated sludge system as part of the effluent treatment process at the facility. Activated sludge systems have a high-level treatment composed of stages of aeration, flocculation, and solids separation (Smook 1989). The system involves circulating activated sludge continuously to provide a constant supply of nutrients and biological organisms necessary for treatment. The term waste activated sludge (WAS) refers to excess sludge removed from the system to reduce chances of nutrient and biological imbalances in the process. Once the effluent has undergone secondary treatment it can then go through a set of sedimentation basins called clarifiers, where suspended solids settle out of the effluents, the remaining final treated effluent (i.e., KPME) can then be discharged to a river or surface water body. Irrigation with either one of the three effluents would be considered a tertiary stage of effluent treatment.

7.2 PROJECT OVERVIEW

This project had two components: (1) three growth chamber studies and (2) a five-year field study. The three growth chamber studies were designed to address: (1) using KPME as a source of irrigation water compared to ME; (2) the impact rainfall, simulated using distilled water, might have on the effluent loading rates of various elements; and (3) the effect calcium amendments might have in combination with rainfall on the impacts on soil chemical properties resulting from KPME applications. The field study addressed the impacts KPME applications would have on soil chemical properties under field conditions. For the field study, no soil amendments or fertilizers were applied.

Application rates of the water, effluent, and water/effluent combinations used in the growth chamber studies included the daily equivalents of 1.5, 3, 6, and 9 mm d^{-1}, while the field component applied rate was 3 mm d^{-1}. The amount of effluent or water applied in the growth chamber studies were 2 to 3 times higher than the annual precipitation for the study area (Environment Canada, 2005). Careful irrigation management strategies would be necessary at the field location, which contained coarse textured Brunisols to avoid excessive throughflow of potential contaminants to the underlying groundwater. One management option would be intercropping forage species amongst the planted hybrid poplar to minimize possible groundwater issues. The growth chamber studies identified both extreme and possible upper limits for the use of KPME as a source of supplemental water when applied with the right management conditions. Historically, the region where the study soil was collected and where the field study was conducted receives approximately 340 mm, roughly equivalent to approximately 2.7 mm d^{-1} from May to mid September. During this period potential evapotranspiration rates were estimated to range from 3 to 5 mm day^{-1}, resulting in daily water deficits from 0.3 to 2.3 mm throughout the growing season. This deficit could be overcome by irrigation with KPME. Even at these rough estimates, the rate of KPME required to provide the necessary water to meet this demand would be slightly lower than the COMB-25 and COMB-50 (25:75 and 50:50 effluent:water) combination treatments applied at 6 mm d^{-1} in two of the three growth chamber experiments. Even at these rates, the resulting soil solution ECs and SAR were within tolerable limits of many crops, including some clones of hybrid poplar (Shannon et al. 1999; Wentz 2001). The equivalent application of 2.5-3 mm d^{-1} of KPME throughout the growing season is unlikely as this assumes there would be a daily deficit of 2.3 mm d^{-1} for the entire growing season; this is unlikely, but not impossible for this area.

The growth chamber experiments used in this study provided insight into the upper limits for various irrigation scenarios. A more realistic scenario is where deficits may occur for only a few weeks during the season, although the short term daily deficit would likely exceeded 2.3 mm d^{-1}. Figure 14.1 shows calculated potential evapotranspiration (PET) and precipitation received from 2003 to 2005 during the growing season (May 1 to Sept 30).

7.3 IRRIGATION WITH KRAFT VERSUS MUNICIPAL EFFLUENT

Depending on the treatment stage from where effluent samples are taken, Kraft pulp mill effluents have compositions comparable to municipal effluents. Waste activated sludge typically will have concentrations of nitrogen and phosphorus comparable to municipal effluents, but have higher concentrations of suspended solids (3-6%) and organic matter within the waste stream. Through dewatering, aeration, and biological treatment, the amount of suspended solids, organic matter, and nutrients (i.e., N and P) are reduced in the effluent, making it comparable to municipal effluents, except for higher coneentrations of HCO_3^- and dissolved Na^+, Cl-, and SO_4^{2-}. The latter three ions pose the greatest concern for irrigation, especially the combination of Na^+ and HCO_3^-. Of these solutes, only Cl^- and Na^+ have guidelines for use for irrigation. Considering water quality for agricultural uses (CCME 2006), only Cl has a guideline, which ranges from 100-700 mg L^{-1} but largely depends on the crop being grown to avoid foliar damage. In this study the Cl^- content within the effluents used should not have posed a problem for crop tissue. The soil solution extract Cl^- within the soil will reduce osmotic potentials and create salinity issues negatively affecting crop growth.

The impact of excess Na is, however, quite different. While Na does not have a guideline for plant toxicity, it creates soil problems such as crusting and reductions in water infiltration. Issues can arise when the SAR of irrigation waters increases. In addition to SAR, effluent salinity and alkalinity (i.e., HCO_3^- and CO_3^{2-}) need to be considered in addition to texture of receiving soil. Increasing effluent salinity can reduce the potential for soil dispersion, but irrigating with large volumes of low salinity water can have the opposite effect. The drawback of Kraft pulp mill effluents is the high HCO_3^- concentrations. Calcium and Mg^{2+} bicarbonates are soluble in water, however, as soils begin to dry; HCO_3^- can begin to precipitate out of solution forming insoluble $CaCO_3$ and $MgCO_3$. As a result, the negative effects of high Na^+ concentrations are amplified.

In this study both municipal and Kraft pulp mill effluents were studied to compare their effects on soil chemical properties and the growth and nutrient uptake of both reed canarygrass and hybrid poplar. Biomass increases for both reed canarygrass and hybrid poplar were limited by application rate, but increasing the rate lead to increased soil salinity and sodicity. Leaf drop by the hybrid poplar was observed at the highest application rate, most likely attributed to the increase in soil salinity. Municipal and secondary Kraft effluents (i.e., WAS) were comparable in their ability to provide nutrients like N, P, K, and S. Waste activated sludge also resulted in the greatest increase in soil solution EC and SAR within the amended soils. WAS is similar to KPME, which would be expected as they are from the same waste effluent stream, collected at different stages of treatment. At the highest application rate, roughly two to three times higher than the average PET for the area from where the soil was collected, there was a 3-5 fold increase in soil solution EC and a 12-16 fold increase in soil solution SAR when both Kraft effluents were used as a source of irrigation water compared to water. Compared to the control, even at the lowest rate, the magnitude of the increase in soil solution SAR, because of the Kraft effluents, was in the same range but only a two-fold increase in soil solution EC was observed. The effluent provided the only water supplied to the reed canarygrass and hybrid poplar; this would not be the case under field conditions. In the field, seasonal precipitation would supply additional water to the crop and alter the distribution of solutes and nutrients within the rooting zone. In addition to coarse textured Brunisols, the area where the field study was conducted also contains finer textured soils such as Luvisols as well as some Gleysols in lower lying areas. The use of Kraft effluents as an irrigation source on these soils may be limited due to the higher clay content making them more prone to dispersion, resulting in greater reductions of infiltration rates. Further work should be conducted on these types of soils to evaluate the possible effects and mitigation options like amendments or effluent:water combinations.

7.4 EFFECT OF DILUTING KRAFT EFFLUENT

Under the growing conditions of the growth chamber study used, comparing Kraft and municipal effluents, the rates used were limiting to the growth of both the reed canarygrass and hybrid poplar. However, increasing the application rates lead to increased soil solution salinity and sodicity. One possible management alternative is to dilute the effluent. For effluent irrigation projects, dilution of effluent streams could be accomplished by: (1) diluting or blending effluent with an additional water source or effluent right at the source or in the field during an irrigation event; (2) supplementing or alternating irrigation events with an alternate water source; and (3) dilution of effluent irrigation by precipitation. The second growth chamber study addressed two questions: the first regarding the rate limitation, the second what the effect might be on soil chemical properties and hybrid poplar growth if effluent applications were diluted. For the purposes of this experiment, distilled water was chosen as the water source to dilute the effluent, as it would be more comparable, than municipal, treated water, to water received through precipitation.

The combination of distilled water with KPME increased the biomass and height of hybrid poplar compared to KPME treatments and the DW treatment at 1.5 mm d^{-1}. At 6 mm d^{-1}, biomass and height were comparable to the DW treatment. Leaf drop was observed in KPME treatments at both rates. Diluting KPME effluent with DW increased soil solution SAR and EC to levels considered "Fair" according to Provincial guidelines at both rates. While small increases in soil solution extracts of K^+, Ca^{2+}, and Mg^{2+} were observed in the soil, Na^+, Cl^-, and SO_4^{2-} continue to remain major contributors to soil solution EC and SAR. Higher concentrations of HCO_3^- will also continue to plague these type of systems as additional Ca^{2+} and Mg^{2+}, not only in the effluent streams but in the receiving soils as well, will be precipitated, further amplifying Na^+ related issues.

Biomass of the winter wheat within unamended soils increased because of the combination treatments. These DW/KPME/WAS treatments reduced the concentrations of soluble salts applied relative to just applying KPME, but also applied supplemental N and P contained within the WAS. While DW was used to reduce the concentration of salts applied through KPME and WAS applications, KPME and DW had the same effect on WAS. However, in this case both KPME and DW increased the water content of the WAS slurry, which would be beneficial under field conditions to reduce chances of solids plugging sprinkler nozzles or accumulating within an irrigation distribution system. Waste activated sludge was "diluted" within the various combination treatments; it still provided additional nutrients that resulted in greater biomass of wheat irrigated with any of the combination treatments, at even the lowest dilution, with KPME. However, except for soils irrigated with DW, only the two lower combination treatments had soil solution SAR less than 10, and all treatments had soil solution ECs less than 2 dS m^{-1}.

7.5 CALCIUM BASED SOIL AMENDMENTS

Effluents require different management strategies depending upon their chemical content. For Kraft pulp mills, managing Na^+ and salinity levels of effluents will need two approaches: one long term, the other short term. Long-term Na^+ life cycle analyses or a system approach to Na^+ reduction in the effluent stream should be evaluated. There may be opportunities to divert other waste streams, which contribute significantly to the concentrations of Na^+, Cl^-, and SO_4^{2-} out of the effluent system; this may include chemical or filtration technologies. Short term, the use of elemental S or Ca-based soil amendments like $CaCl_2$ or $CaSO_4$ may be options or possibly even acidification of the effluent stream to deal with high concentrations of HCO_3^-. However, over the long term they could be more costly should organizations pursue these options independently, but could be less costly under joint venture or partnership arrangements. These could be advantageous, especially under scenarios where a by-product generator (i.e., elemental S, phosphogypsum, lime, etc.) could be partnered with a by-product user, like an effluent irrigation management program.

Gypsum amendments can be incorporated into effluent irrigation projects to deal in the short term with Na applied through effluents. Various Ca^{2+} amendments like $CaCl_2$, $CaSO_4$, wood ash, or manures could be used in conjunction with sodic effluents for this purpose. Near large communities, a significant amount of wallboard is landfilled on an annual basis, consisting primarily of waste paper and $CaSO_4$. Pulp and paper mill companies conducting water purification or operating cogeneration facilities produce a significant amount of waste products, which are also Ca-based, including lime, wood ash, and bark ash. Ca-based soil amendments were incorporated into soils and various combinations of DW and Kraft effluents applied to assess impacts on soil chemical properties, nutrient uptake, and biomass of winter wheat. Only the application of gypsum lessened the increase in soil solution SAR. The CO_3^{2+} and high pH of the wood ash combined with the HCO_3^- content of the effluents most likely negated any positive effect the Ca^{2+} added in the ash may have had. Coupling cyclic irrigation strategies with intercropping and organic matter or Ca amendments may also help further reduce soil sodicity. Decomposition of organic matter helps mobilize Ca^{2+} by increasing the concentration of organic acids and CO_2 in the soil solution, increasing the solubility of $CaCO_3$ (Sekhon and Bajwa 1993; Mishra et al. 2004). The combination of Ca-based soil amendments and diluted Kraft pulp mill effluents applied at rates more realistic to that which would be utilized in the region (i.e., < 3 mm d^{-1}) where the Kraft pulp mill is located could allow Kraft pulp mill effluents to be used as a source of supplemental irrigation water. In this sub-humid region, precipitation received in the spring and in the fall after harvest can flush the root zone of salt ions (Sharma et al. 1994). However, excessive leaching of dissolved salts through the rootzone can pose potential groundwater issues especially should high concentrations of Cl^- or SO_4^{2-}, or other contaminants, begin to reach the groundwater.

7.6 IMPACT OF REGIONAL PRECIPITATION ON KPME APPLICATIONS

Over a five-year period, a study was conducted to evaluate the impacts regional precipitation would have on KPME applications. Kraft pulpmill effluent was applied for three years followed by two years of no irrigation. In the field study, three irrigation treatments (i.e., not irrigated, water, and KPME) were used with two vegetation treatments (i.e., hybrid poplar only and hybrid poplar intercropped with timothy and alsike clover) to evaluate what effect regional precipitation and KPME applications would have on soil chemical properties.

After three years of irrigation followed by two subsequent years without irrigation, the amount of KPME applied represented 11.7% of the total water received, consisting of 300 mm of irrigation water or effluent plus an additional 2,274 mm of total precipitation (i.e., rainfall and snowfall). By the end of this period, soil solution SAR and EC remained elevated in soils irrigated with KPME while those of soils irrigated with water were comparable to baseline levels. Soil solution concentrations of Na^+ peaked after Yr-2 and gradually started to decrease at the surface but began increasing at depth as Na^+ was leached through the profile. SAR tended to peak the year after the peak Na values were observed. Soil solution concentrations of Ca^{2+} and Mg^{2+} decreased drastically at the surface between Yr-2 and Yr-3, possibly from the precipitation as soils dried at the surface. However, solution concentrations of both Ca^{2+} and Mg^{2+} significantly increased at depth, evidence of displacement, and subsequent leaching. Similar observations were made for solution concentrations of Cl^- and SO_4^{2-}.

Soils at this site after three consecutive years of irrigation, based on SAR, would be rated as "fair", but would be categorized as "good" after two subsequent years of no irrigation (Alberta Environment 2001). Even after the two-year period of no irrigation, soil solution levels of Na remain elevated. The increase of soil solution extracts of Na^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} at lower depths indicates leaching is occurring more readily than at a similar site with clay textured soils. While this is positive in order to avoid accumulation of salts within the rooting zone, nutrient management, and possible groundwater issues, will pose challenges. The addition of Ca-based amendments like gypsum to this site would be necessary to displace Na^+ from the surface soils.

7.7 SUSTAINABILITY

Unless the concentration of Na^+ within Kraft effluent can be reduced, the long-term use of KPME effluent as a source of irrigation water will be limited as on-going irrigation with Kraft effluents would most likely lead to excessive increases of Na^+ within the rooting zone. The use of Kraft effluents could be possible if the Na^+ and HCO_3^- concentrations within the effluents could be reduced. Howe and Wagner (1999) showed that even after more than 10 years the Na^+ has remained in soils irrigated with pulp mill effluent, but this was dependent on the difference between precipitation and actual evapotranspiration (AET). While precipitation may provide some leaching, it also can result in surface crusting reducing infiltration. A delicate balance needs to be struck between managing effluent chemistry and managing receiving soils.

In addition to dealing with the effluent chemistry, cost and distribution of the effluents will be the next issue needing to be dealt with. However, a series of storage ponds and / or wetlands could be constructed to provide effluent storage, and possible additional treatment in the case of the wetlands. Effluent levels could be maintained by pumping effluent overland during the irrigation season or possibly during the winter. Implementing cyclical or supplemental irrigation strategies may be the option most appropriate for the use of KPME as a source of irrigation water.

7.8 ALTERNATIVES

One strategy to deal with Na^+ impacts involves end-of-pipe solutions, namely those options that are implemented after effluent has gone through the final stages of treatment or has been discharged. The success of these depends on volume of effluent produced and the seasonal irrigation requirements. End-of-pipe solutions are processes which are implemented or occur downstream of the effluent treatments process and/or applications at the site if that is a feasible option. These options include: (1) acidification of effluent streams to manage CO_3^{2-} and HCO_3^- and reduce concentrations and (2) adding amendments like $CaCl_2$ to the effluent to reduce high SAR and increase ionic concentration and electrical conductivity of the effluent. The continued application of Ca and Mg amendments like gypsum, lime, ash, or organic amendments like manures or biosolids can become costly (Howe and Wagner 1996; Bauder and Brock 2001) unless they are either cheap or produced locally. Should high application rates of these amendments be required they may be suitable alternatives, in the short term, but long term other solutions should sought if irrigation is to be sustainable.

In many ways, upstream manipulation of effluents produced by industry is more easily achievable than that by municipalities. Industry has more control over sources of waste contributing to effluent quality unlike municipal effluents that can be quite variable and are dependent on the attitudes of upstream users (e.g., citizens and businesses). Depending on the issue, societal pressures can result in significant changes that can result in downstream improvements. One example is phosphate. Sodium phosphate was for many years used to increase the cleaning power of soaps and detergents. These products were used on a daily basis for cleaning; however, excess phosphate lead to excessive algal growth and eutrophication (Schindler 1974). Biodegradeable products, while some still contain phosphates, contain significantly less than before.

Another example in industry is the use of elemental chlorine for the bleaching process for pulp and paper. Public pressure has led to the move away from the use of elemental chlorine for bleaching to alternatives like chlorine dioxide (ClO_2) or ozone. Pressure to reduce anthropogenic sources of chlorinated organic compounds and their release into the environment lead to the change, with the ClO_2 and ozone having less environmental impact than elemental Cl (McNamara, personal communication). Life cycle analyses of effluent stream inputs can provide insight into areas within a mill or effluent treatment system where additional reductions in Cl^- and Na^+ could take place. Ions like Cl^- and Na^+, because of their solubility, can be difficult to deal with. Options like desalinization are expensive and often not considered for treatment of effluents for use within irrigation projects (Beltran 1999).

7.9 IRRIGATION MANAGEMENT

Irrigation management such as frequency, scheduling, and crop selection will play an important role as effluent irrigation projects develop. Climatic and environmental conditions will influence the choices on when and how long to irrigate, what crop(s) should be grown, and what the end use of the crop(s) might be.

Supplemental irrigation programs could provide an alternative management strategy for sub-humid climates where effluents can be incorporated into existing irrigation programs to supplement existing water sources (Fereres and Soriano 2007). Effluents could be used during the irrigation season to provide supplemental water and nutrients during peak growth periods with better quality water being used to help manage salinity issues. Deficit irrigation strategies may not be entirely desirable since irrigation supplies water at rates lower than a crop's evapotranspiration since this would increase the possibility of soil salinization or sodification (Fereres and Soriano 2007).

Selecting crops tolerant of salinity may be an option with many tree and crop breeding programs providing wide selections of crops tolerant to certain environmental and climatic conditions (Table 8.1 and Table 8.2, Appendix – A). This option can also fit into a short-term solution. If soil salinity or sodicity is allowed to increase, the options available with respect to crop selection decrease. The added benefit of increased yields in the short term may be appealing, but when considering the longer-term impacts on soil chemical properties or groundwater quality, alternatives to irrigation need to be considered.

Agroforestry systems, such as intercropping, could be viable alternatives for maximizing application windows in regions with shorter growing seasons, such as parts of Alberta and other provinces that also experience periods of water deficits during these periods. The integration of selective forage and tree species when grown together, in an effluent management program, under supplemental irrigation would help maximize both water and nutrient usage. While productivity levels, within intercropped systems, may not necessarily be comparable to single monocrop systems early on, this may not be the case. This is only speculative as few studies have evaluated long-term (i.e., >5 yrs) effluent irrigation management programs that have also involved intercropping, as compared to monocropping of forages, cereals, or trees alone.

The use of agroforestry systems, such as alley or row cropping, could be modified to include intensive woodlot management within effluent management programs and tailored to meet specific community or industry needs. For example, communities irrigating densely planted hybrid poplar, willow, or some forage species under effluent irrigation, could use the harvested material as an alternative fuel source, offsetting the need for non-renewable fuel sources and associated costs. These materials could be used to heat community buildings, halls, barns, or on-farm buildings. Longer-term, communities and industries operating effluent management programs involving the irrigation of forage or tree crops like this could provide feedstock materials for other industrial sectors involving the production of bio-products (Wood and Layzell 2003; Fennell and Nilsson 2004; Welling and Shaw 2007; Samson et al. 2008), such as agrifibres and biocomposites (Bowyer and Stockmann 2001), and bio-energy products, like cellulosic ethanol (Madakadze et al. 1999; Geber 2002). Multiple crop systems, like agroforestry, would also diversify market opportunities for the sale or use of the harvested products, not to mention the production of a renewable fuel source.

7.10 FUTURE RESEARCH

Regions with arid to sub-humid climates can adopt the approach taken by arid countries where projects involving effluent irrigation alternatives are considered as investments, rather than costs, with greater emphasis placed on not only financial savings but the environmental benefits as well. Further research needs to be conducted on equipment options, combinations of effluents, amendments, soil conditions, and crop selection so these can be tailored to the right environments. These are especially important under supplemental programs so that irrigation can be timed to achieve optimal yields.

Future research should be conducted on the use of Kraft effluents as a source of irrigation water. Implementation of an irrigation program, at Kraft pulp mills on a large or even small scale, should consider a complete lifecycle analysis any or all waste streams that enter into the effluent stream. In this way, major sodium sources can be identified and the feasibility of reducing or eliminating the Na^+ from these sources examined. Since Na^+ plays an important role in the pulping process, any additional Na^+ recovered capable of being reused also represents a cost savings and value to the program. However, the work should also be extended to other agricultural, industrial, and municipal wastewaters and their implications in management programs that also incorporate the use of multiple cropping systems like agroforestry.

In the past, the availability of potable water sources in Alberta and Canada, for irrigation and recreation use has allowed less focus to be placed on effluent reuse and treatment, as compared to work done on water treatment. In recent years, this has begun to change and the focus has begun to shift to evaluate management options available for effluents. Quite often the limiting factor in conducting these projects is cost, however, multifaceted approaches should be taken not only to address economic and environmental costs, but also the associated benefits. For example, while the implementation of an irrigation management program would be costly, would the benefits associated with improvements in water quality, nutrient management, and carbon sequestration be capable of offsetting these initial establishment costs? Projects could be established that would not only have economic benefits (i.e., crop resale) but would also have environmental benefits such as improvements to water quality and would also have a positive impact on climate change and carbon sequestration through the generation of renewable fuel sources.

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8. *APPENDIX – A: CROP SALINITY TOLERANCES*

Table 8.1. Relative tolerances of selected crops to exchangeable sodium taken from Ayers and Westcot (1994)

Sensitive (<15 ESP)		Semi-tolerant (15-40 ESP)		Tolerant (>40 ESP)	
Avocado	*Persea americana*	**Clover, Ladino**	*Trifolium repens*	**Alfalfa**	*Medicago sativa*
Maize	*Zea mays*	**Dallisgrass**	*Paspalum dilatatum*	**Barley**	*Hordeum vulgare*
Peas	*Pisum sativum*	**Fescue, tall**	*Festuca arundinacea*	**Beet, sugar**	*Beta vulgaris*
Lentil	*Lens culinaris*	**Lettuce**	*Lactuca sativa*	**Bermuda grass**	*Cynodon dactylon*
Cowpeas	*Vigna sinensis*	**Oat**	*Avena sativa*	**Cotton**	*Gossypium hirsutum*
		Onion	*Allium cepa*	**Wheatgrass, crested**	*Agropyron cristatum*
		Rye	*Secale cereale*	**Wheatgrass, fairway**	*Agropyron cristatum*
		Ryegrass, Italian	*Lolium multiflorum*	**Wheatgrass, tall**	*Agropyron elongatum*
		Vetch	*Vicia sativa*		
		Wheat	*Triticum vulgare*		

Table 8.2. Salt tolerance of various crops modified from Table 2 from Wentz (2001)

Salt Tolerance EC (ds m^{-1})	Field Crops	Forages	Vegetables	Trees, Shrubs
Very High **20**		beardless wildrye fulks altai grass levonns alkaligrass alkali sucatan		
High **16**	kochia sugar beets	altai wildrye tall wheatgrass Russian wildrye slender wheat grass		Siberian salt tree sea buckthorn silver buffaloberry
8	6-row barley sunflower 2-row barley fall rye winter wheat spring wheat	birdsfoot trefoil sweetclover alfalfa bromegrass	garden beets asparagus spinach	hawthorn Russian olive American elm Siberian elm villosa lilac laurel leaf willow
Moderate	oats meadow fescue flax canola	crested wheatgrass intermediate wheatgrass reed canary grass	tomatoes broccoli cabbage	spreading juniper poplar ponderosa pine apple mountain ash
4	corn		sweet corn potatoes	common lilac Siberian crab apple Manitoba maple Viburnum
Low	timothy peas field beans	white dutch clover alsike clover red clover	carrots onions strawberries peas beans	Colorado blue spruce Douglas fir balsam fir cottonwood aspen, birch raspberry
0				black walnut dogwood little-leaved linden winged euonymus spirea larch

9. *APPENDIX – B: WATER QUALITY FOR IRRIGATION*

Table 9.1. Guidelines for interpretations of water quality for irrigation modified from Table 1 in Ayers and Westcot (1994)

Potential Irrigation Problem	Units	Degree of Restriction on Use		
		None	**Slight to Moderate**	**Severe**
Salinity (affects crop water availability)				
EC_w	$dS\ m^{-1}$	< 0.7	$0.7 - 3.0$	> 3.0
(or)				
TDS	$mg\ L^{-1}$	< 450	$450 - 2000$	> 2000
Infiltration (affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)				
SAR $= 0 - 3$ **and EC_w**	=	> 0.7	$0.7 - 0.2$	< 0.2
$= 3 - 6$	=	> 1.2	$1.2 - 0.3$	< 0.3
$= 6 - 12$	=	> 1.9	$1.9 - 0.5$	< 0.5
$= 12 - 20$	=	> 2.9	$2.9 - 1.3$	< 1.3
$= 20 - 40$	=	> 5.0	$5.0 - 2.9$	< 2.9
Specific Ion Toxicity ***(affects sensitive crops)***				
Sodium (Na^+)				
surface irrigation	SAR	< 3	$3 - 9$	> 9
sprinkler irrigation	$me\ L^{-1}$	< 3	> 3	
Chloride (Cl^-)				
surface irrigation	$me\ L^{-1}$	< 4	$4 - 10$	> 10
sprinkler irrigation	$me\ L^{-1}$	< 3	> 3	
Boron (B)	$me\ L^{-1}$	< 0.7	$0.7 - 3.0$	> 3.0
Miscellaneous Effects *(affects susceptible crops)*				
Nitrogen (NO_3 - N)	$mg\ L^{-1}$	< 5	$5 - 30$	> 30
Bicarbonate (HCO_3) *(overhead sprinkling only)*	$me\ L^{-1}$	< 1.5	$1.5 - 8.5$	> 8.5
pH		**Normal Range 6.5 – 8.4**		

Table 9.2. Laboratory determinations for evaluating irrigation water quality problems modified from Table 2 in Ayers and Westcot (1994)

	Parameter	Symbol	Units	Usual range in irrigation water
Salinity				
	Salt Content			
	Electrical Conductivity	EC_w	$dS\ m^{-1}$	0 – 3
	(or)			
	Total Dissolved Solids	TDS	$mg\ L^{-1}$	0 – 2000
Cations and Anions				
	Calcium	Ca^{2+}	$me\ L^{-1}$	0 – 20
	Magnesium	Mg^{2+}	$me\ L^{-1}$	0 – 5
	Sodium	Na^{+}	$me\ L^{-1}$	0 – 40
	Carbonate	CO_3^{2-}	$me\ L^{-1}$	0 – 0.1
	Bicarbonate	HCO_3^{-}	$me\ L^{-1}$	0 – 10
	Chloride	Cl^{-}	$me\ L^{-1}$	0 – 30
	Sulphate	SO_4^{2-}	$me\ L^{-1}$	0 – 20
Nutrients				
	Nitrate-Nitrogen	NO_3-N	$mg\ L^{-1}$	0 – 10
	Ammonium-Nitrogen	NH_4-N	$mg\ L^{-1}$	0 – 5
	Phosphate-Phosphorus	PO_4-P	$mg\ L^{-1}$	0 – 2
	Potassium	K^{+}	$mg\ L^{-1}$	0 – 2
Miscellaneous				
	Boron	B	$mg\ L^{-1}$	0 – 2
	pH	pH	1–14	6.0 – 8.5
	Sodium Adsorption Ratio	SAR		0 – 15

10. APPENDIX – C: WATER AND EFFLUENT PIPER DIAGRAMS

10.1 KRAFT PULP MILL EFFLUENT: 1993-2005

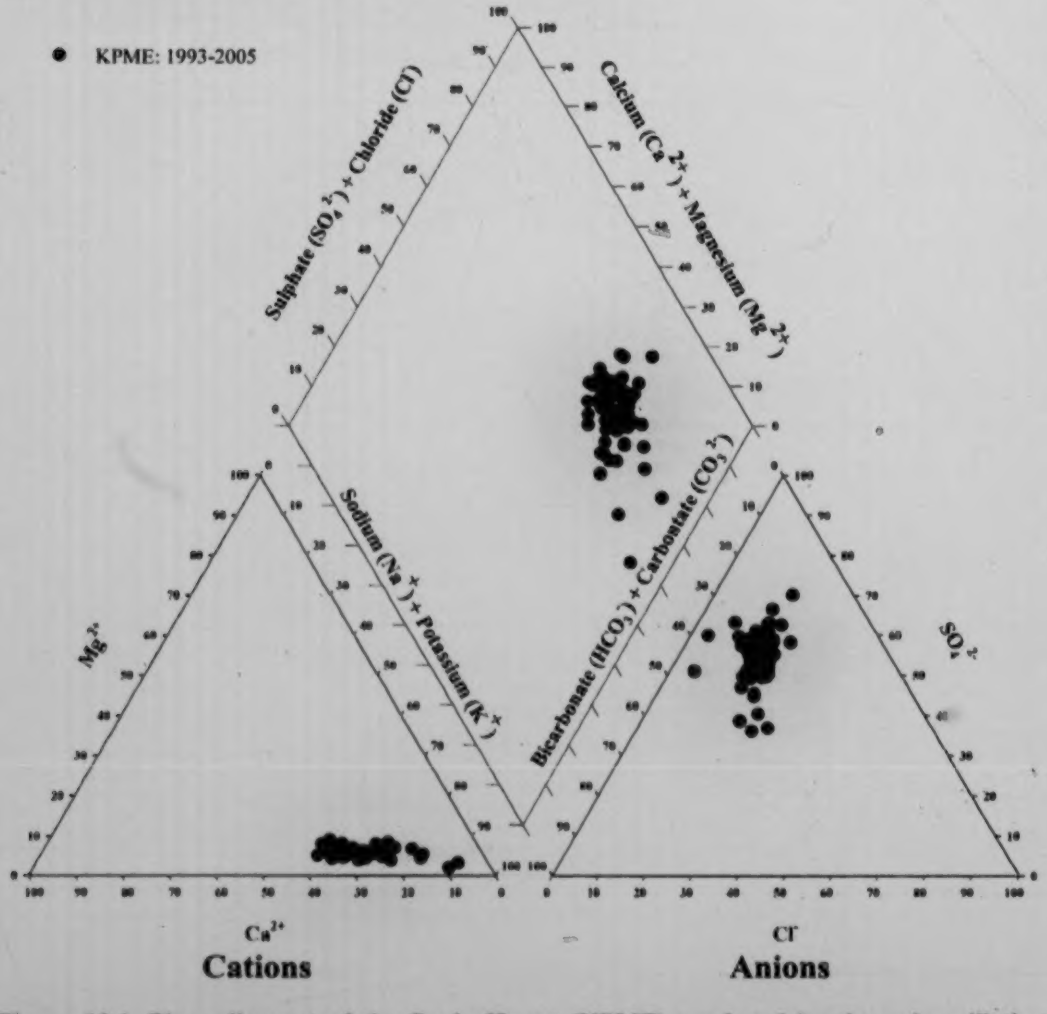

Figure 10.1. Piper diagram of the final effluent (KPME) produced by the pulp mill that provided the effluent for the study. Data show average (n=66) concentrations (mg L^{-1}) of dissolved cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and anions (Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}) in solution. Diagram shows main ions in solution to be dissolved Ca^{2+}, K^+ + Na^+, SO_4^{2-} and HCO_3^-.

10.2 GROWTH CHAMBER & FIELD STUDY: CONTROLS & EFFLUENTS

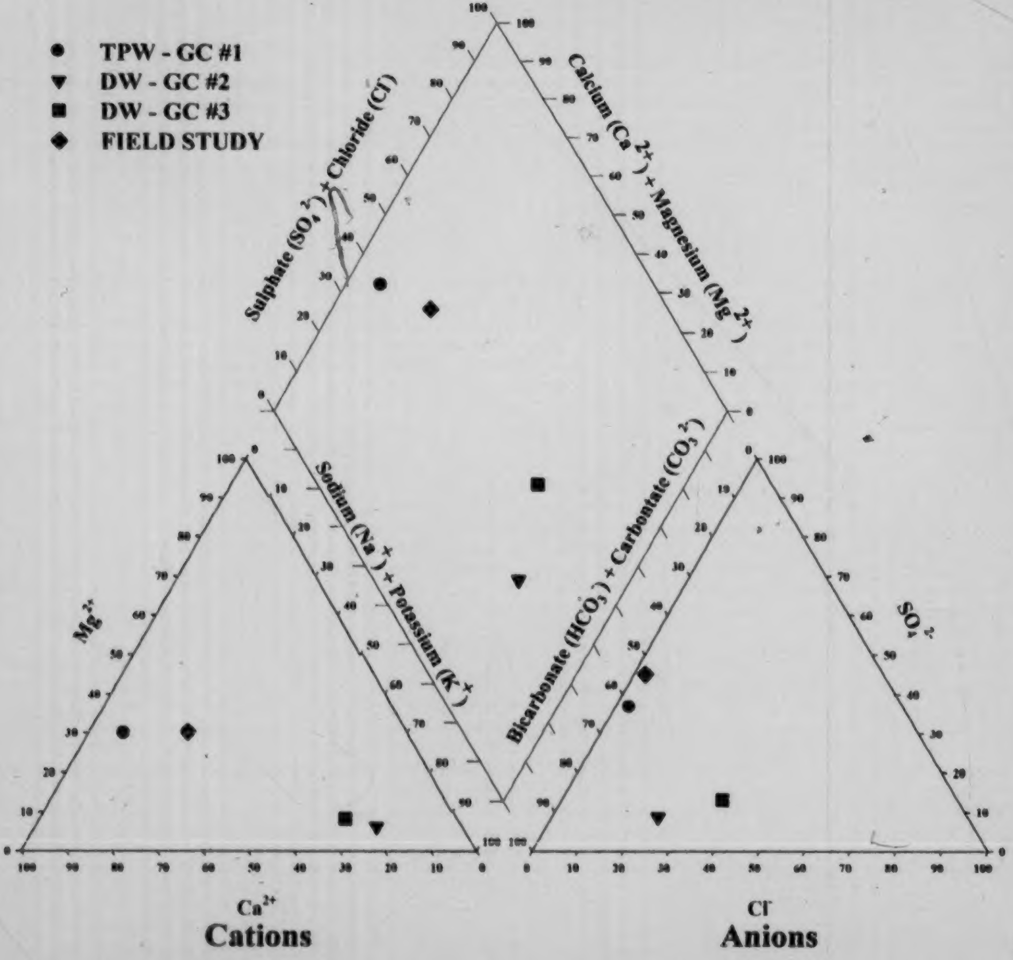

Figure 10.2. Piper diagrams of the controls (TWP and DW; top left used for the three Growth Chamber (GC #1, #2, #3) studies and the Field Study components. Data show average concentrations (mg L^{-1}) of dissolved cations (Ca^{2+}, Mg^{2+}, $K^+ + Na^+$) and anions (Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}) in solution.

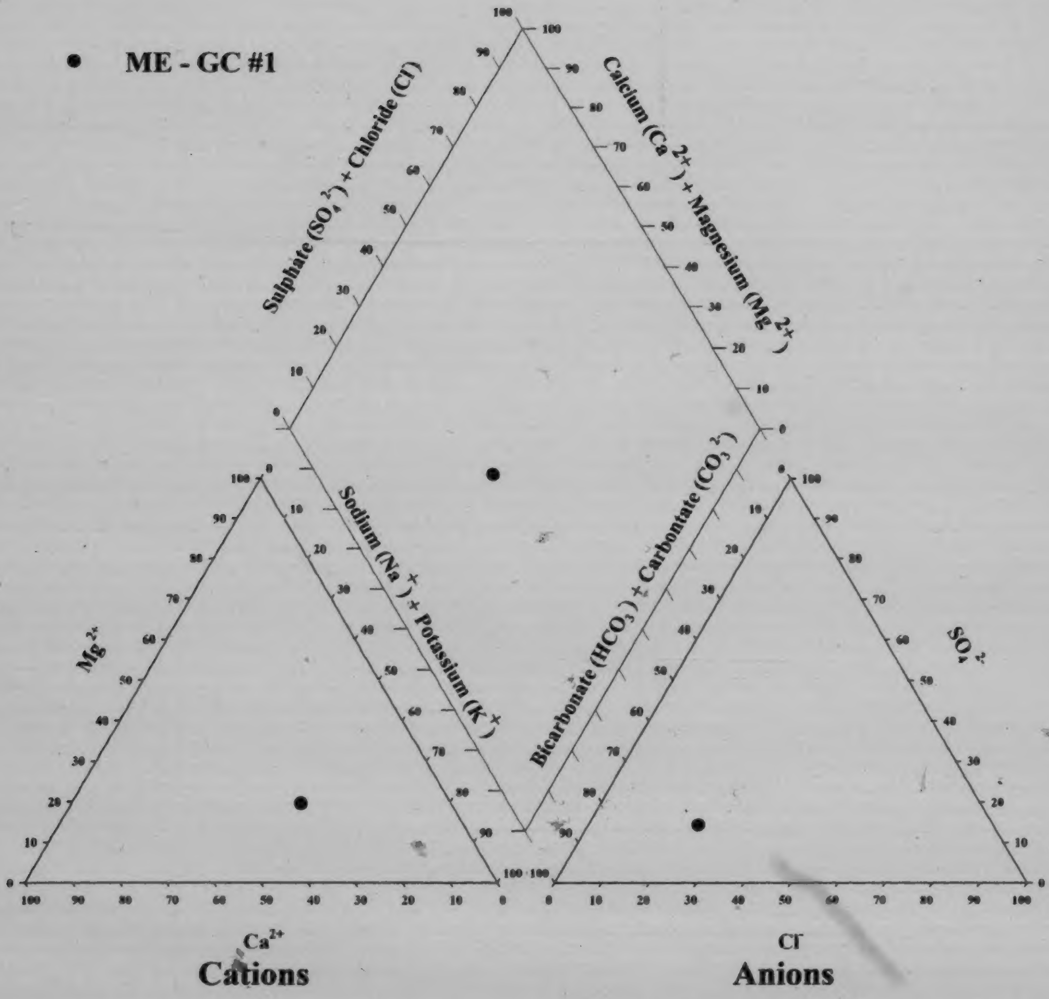

Figure 10.3. Piper diagrams of the municipal effluent (ME) used for the first Growth Chamber (GC #1) study component. Data show average concentrations (mg L^{-1}) of dissolved cations (Ca^{2+}, Mg^{2+}, $K^+ + Na^+$) and anions (Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}) in solution.

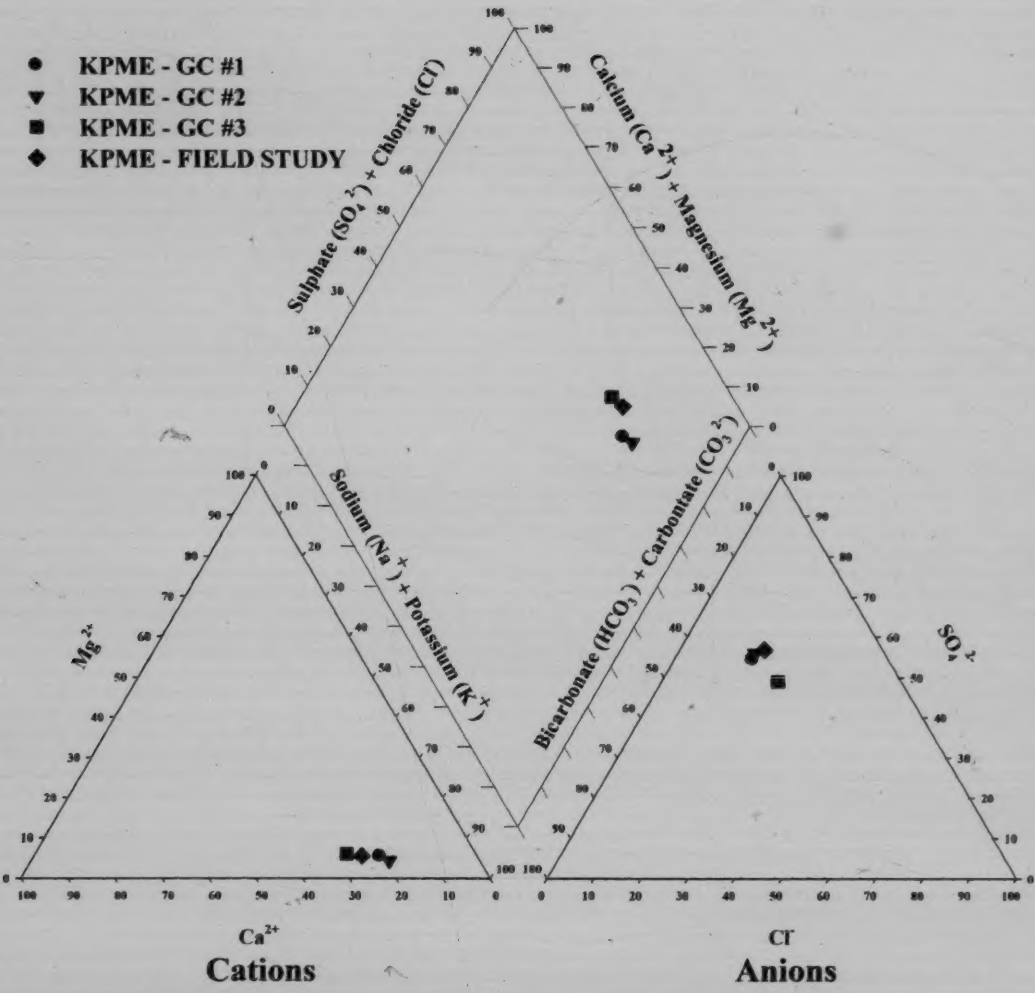

Figure 10.4. Piper diagrams of the Kraft pulp mill final effluent (KPME) used for the three Growth Chamber (GC #1, #2, #3) studies and Field Study components. Data show average concentrations (mg L^{-1}) of dissolved cations (Ca^{2+}, Mg^{2+}, K^+ + Na^+) and anions (Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}) in solution.

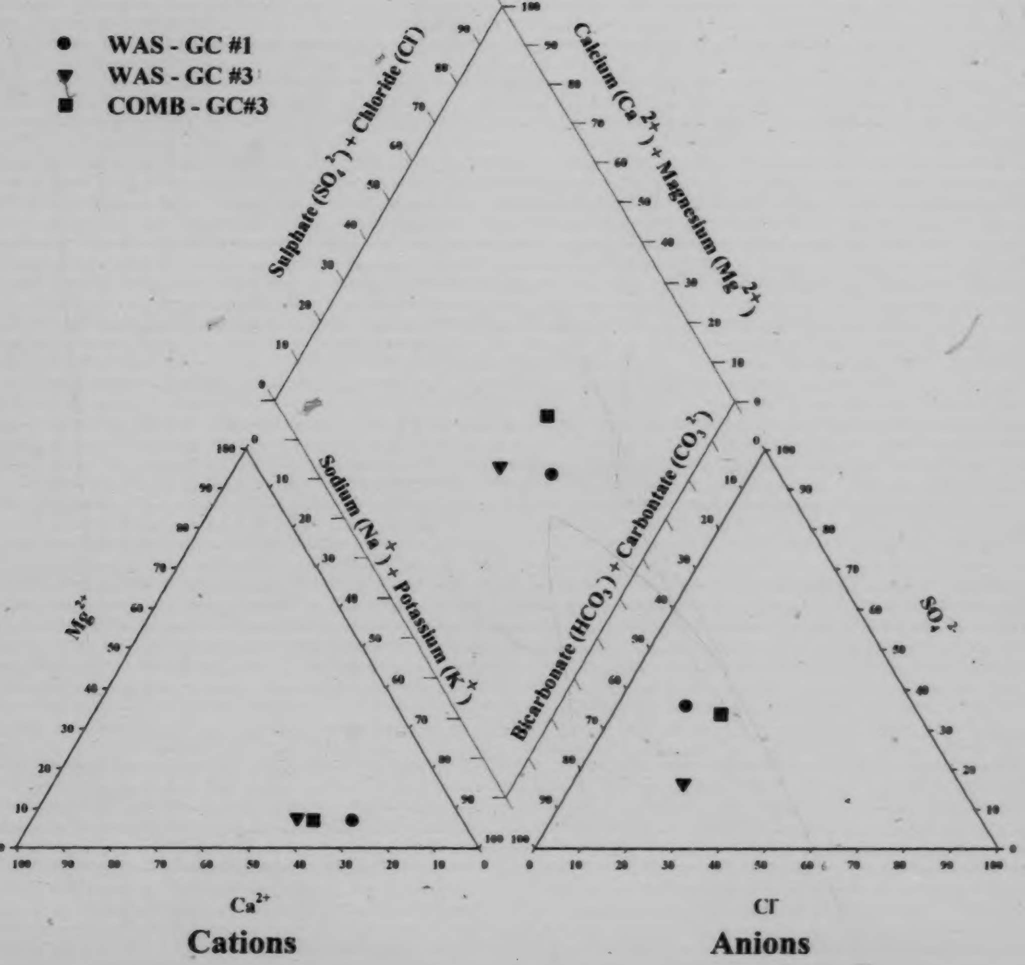

Figure 10.5. Piper diagrams of the combination (COMB) and waste activated sludge (WAS) used for the three Growth Chamber (GC #1, #2, #3) studies. Data show average concentrations (mg L^{-1}) of dissolved cations (Ca^{2+}, Mg^{2+}, K^+ + Na^+) and anions (Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-}) in solution.

11. *APPENDIX – D: PULP MILL EFFLUENT TREATMENT SYSTEM*

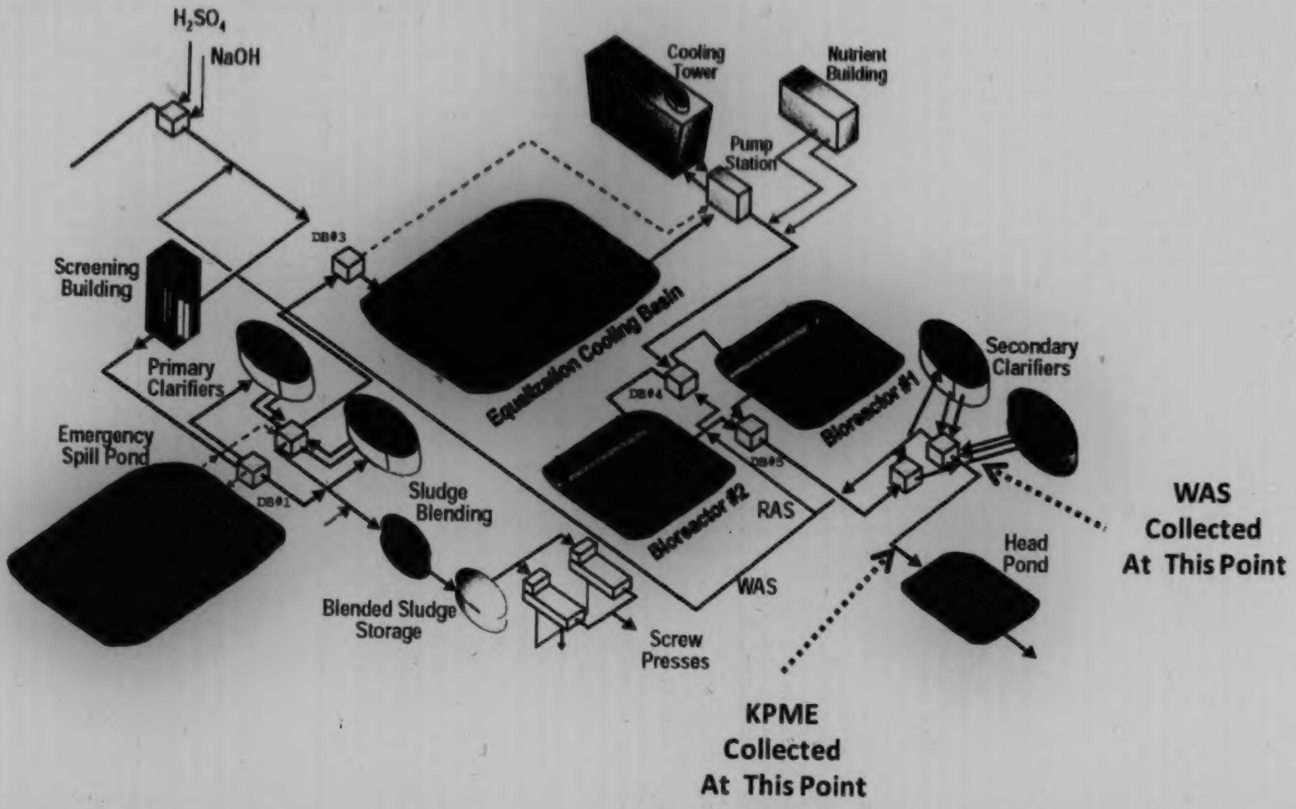

Figure 11.1. Schematic of the effluent treatment system used by the pulp mill which supplied the pulp mill effluents used in this study. Diagram also shows locations where KPME and WAS were collected from the system (Reprinted with the permission of Alberta-Pacific Forest Industries)

12. *APPENDIX – E: PHOTOS FROM THE GROWTH CHAMBER AND FIELD STUDIES*

12.1 GROWTH CHAMBER STUDY #1

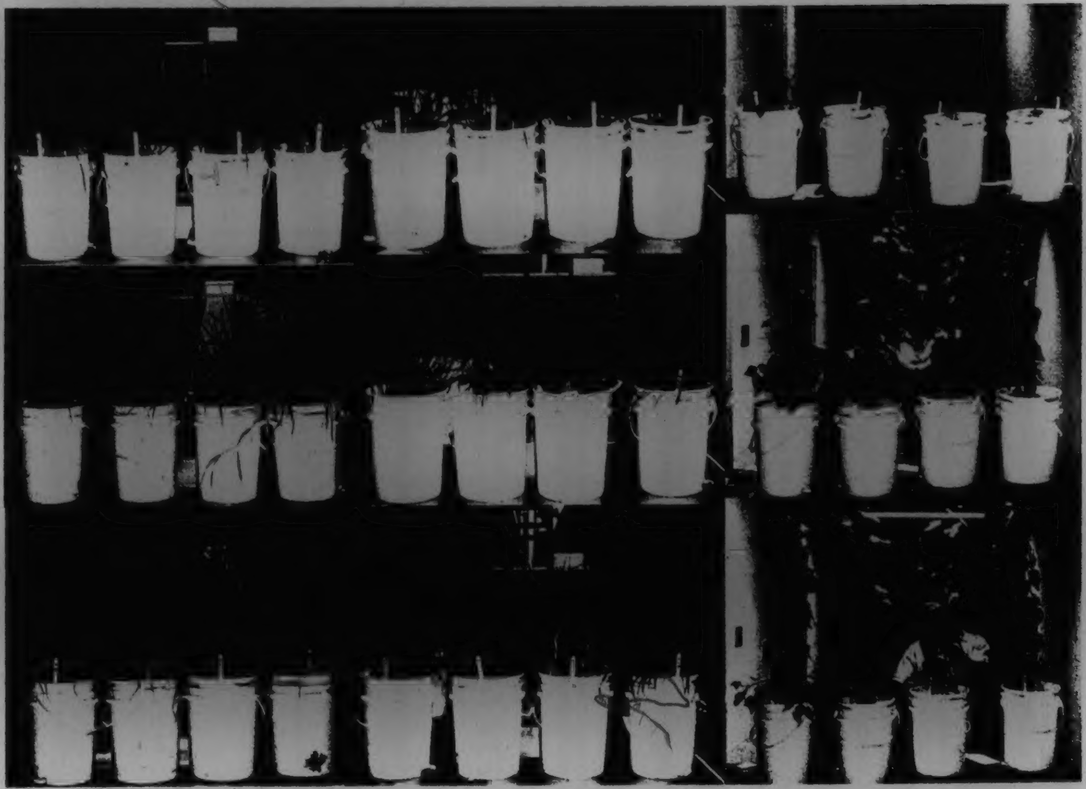

Figure 12.1. Reed canarygrass from 1st cut (figures on left), 2nd cut (middle figures), and hybrid poplar (figures on right) irrigated with (from left to right) TPW (Control), municipal effluent (ME), Kraft pulp mill effluent (KPME), and waste activated sludge (WAS) at application rates of 1.5 mm d^{-1} (top figures), 3 mm d^{-1} (center figures) and 6 mm d^{-1} (bottom figures).

12.2 GROWTH CHAMBER STUDY #2

12.2.1 Column Designs

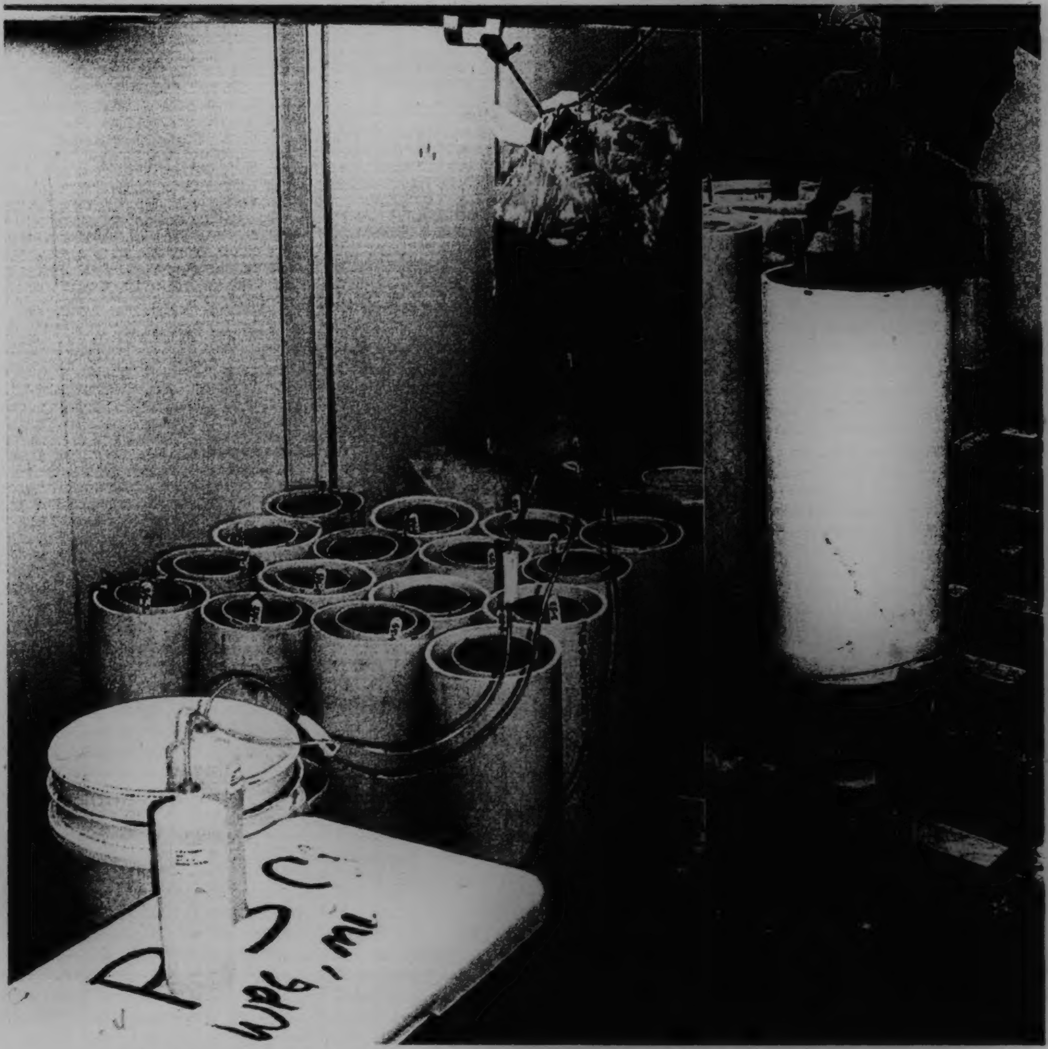

Figure 12.2. Figure shows method of leachate collection. Leachate was collected (figure on left) using Seamless$^{\text{TM}}$ flip top feeding bags attached to the bottom of each PVC tubing (figure on right)

12.2.2 Hybrid Poplar

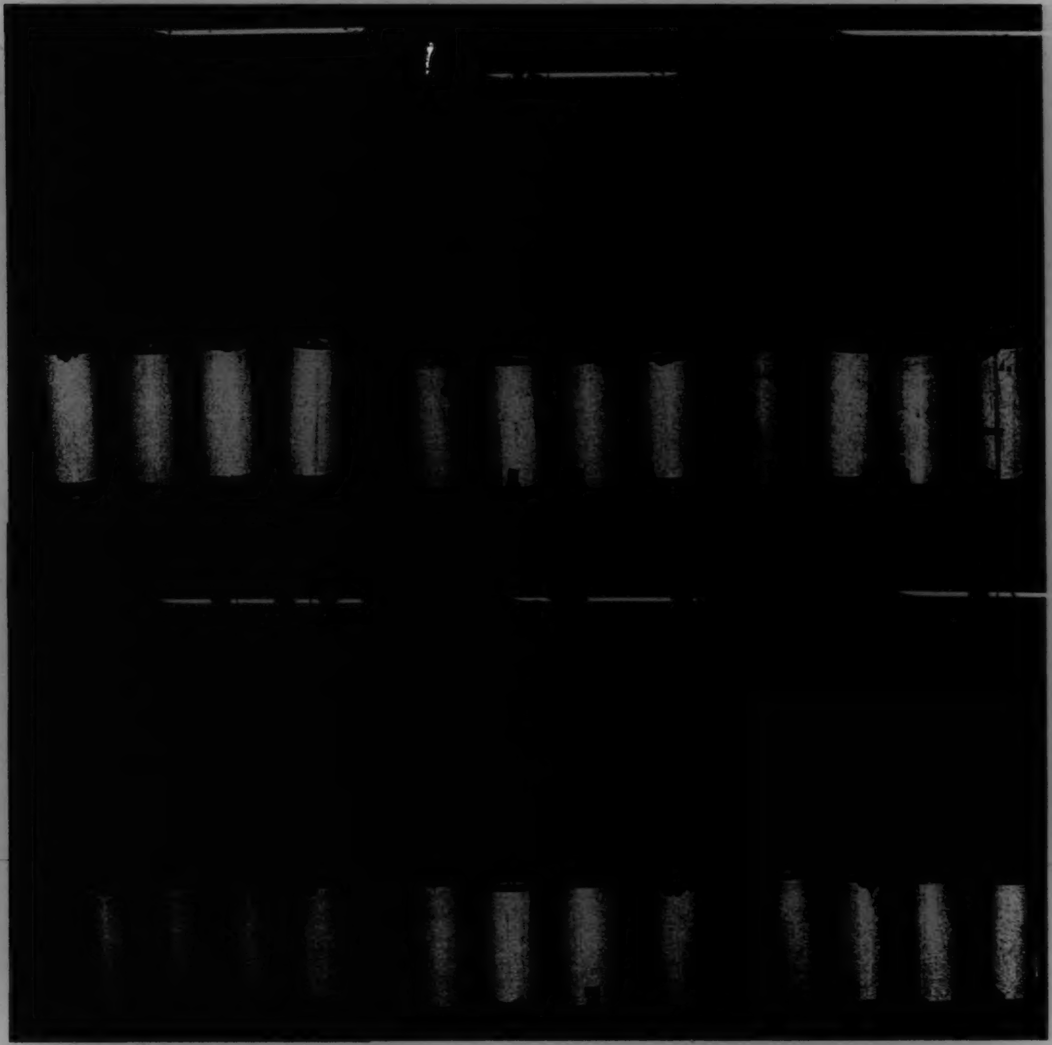

Figure 12.3. Hybrid poplar irrigated (from left to right) with DW (control), combination (COMB), and Kraft pulp mill (KPME) at application rates of 6 mm d^{-1} (top figures) and 9 mm d^{-1} (bottom figures)

12.3 GROWTH CHAMBER STUDY #3: WINTER WHEAT

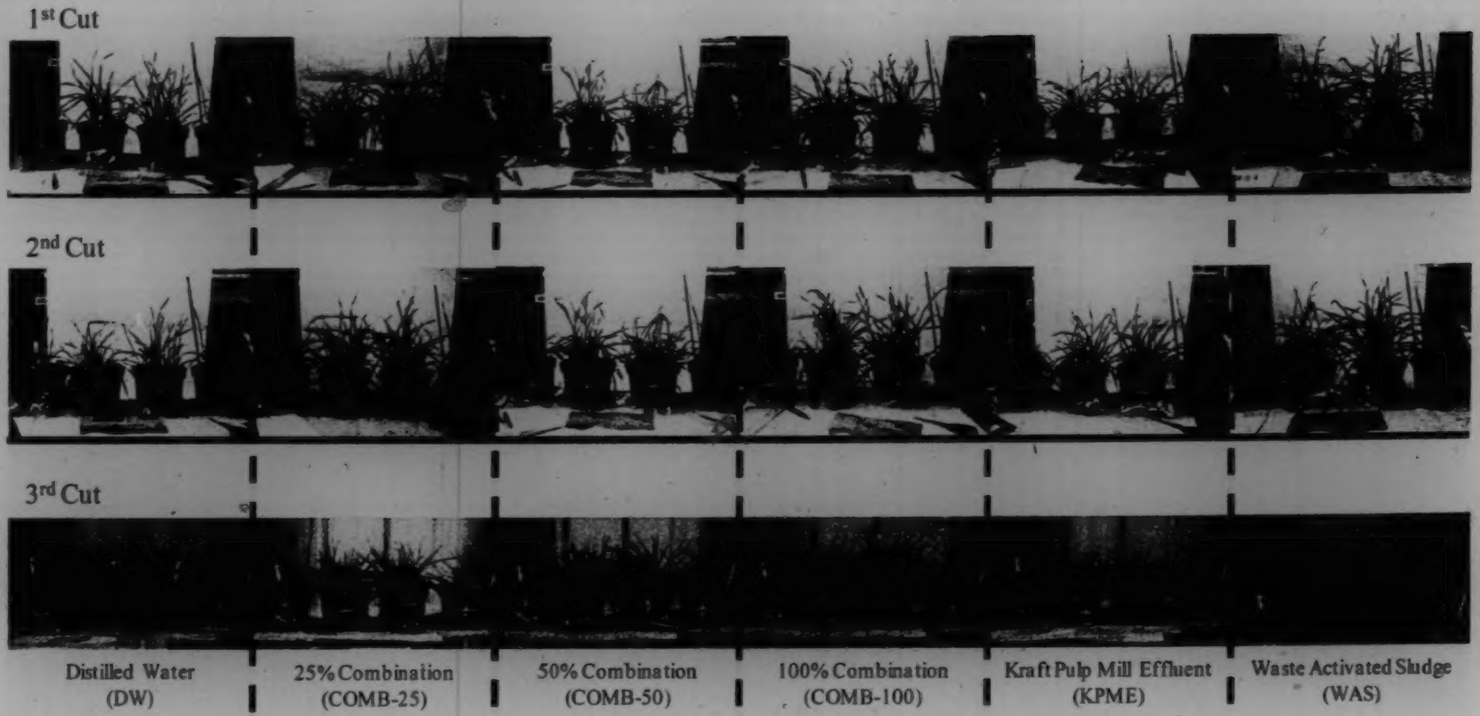
1st Cut
2nd Cut
3rd Cut
Distilled Water (DW)
25% Combination (COMB-25)
50% Combination (COMB-50)
100% Combination (COMB-100)
Kraft Pulp Mill Effluent (KPME)
Waste Activated Sludge (WAS)

Figure 12.4. Winter wheat from each of the three cuts (top to bottom: 1st cut, 2nd cut, and 3rd cut) grown on soils irrigated (from left to right) with DW (control), combination (COMB-25, COMB-50, and COMB-100), Kraft pulp mill (KPME), and waste activated sludge (WAS) grown on unamended, gypsum-, and ash-amended soils. Within each figure, (from left to right) amendment treatments are unamended, gypsum-amended, ash-amended, and unamended soils.

12.4 FIELD STUDY

12.4.1 Soil Profiles

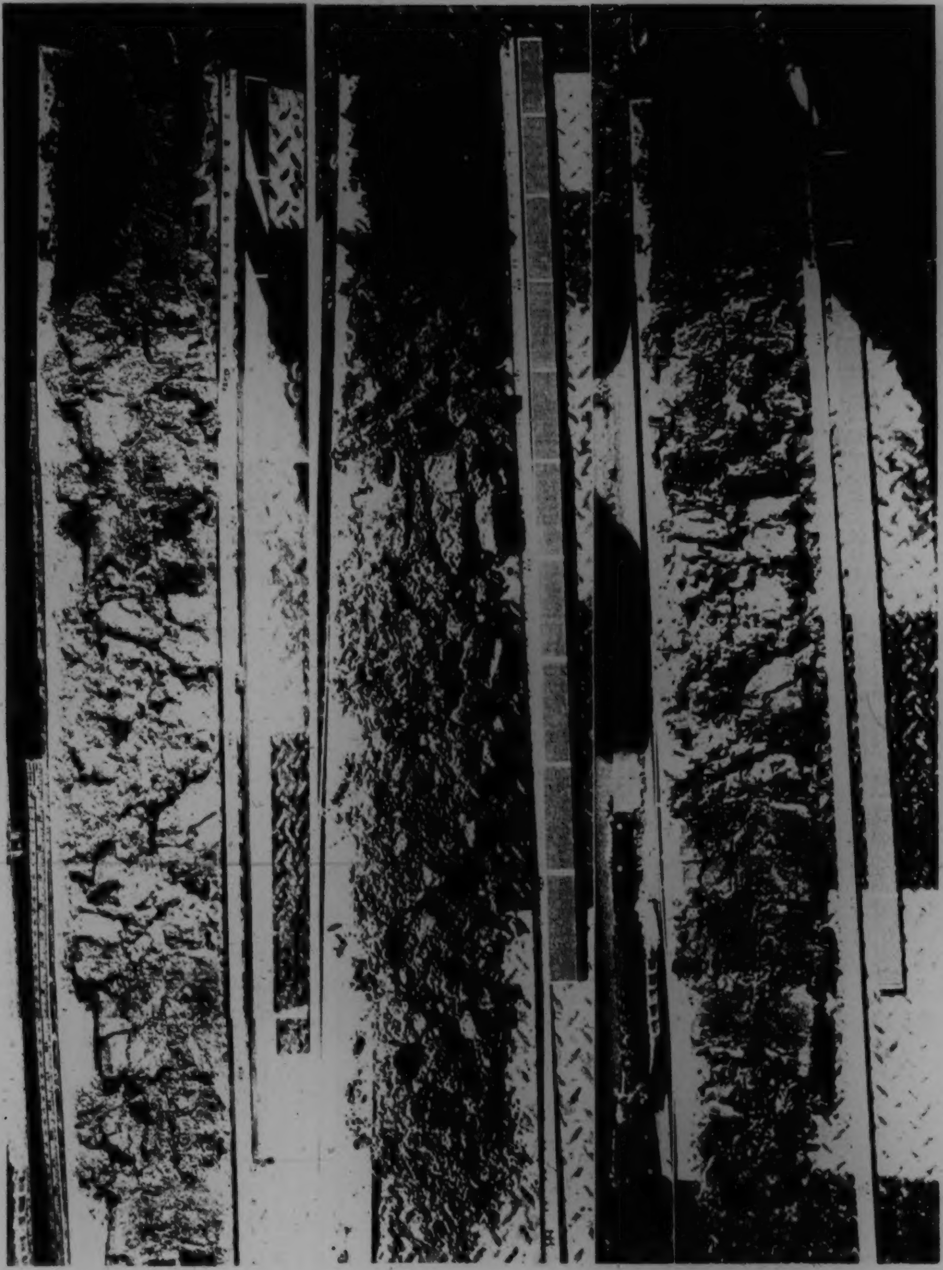

Figure 12.5. Three soil cores from the field site removed from around field site

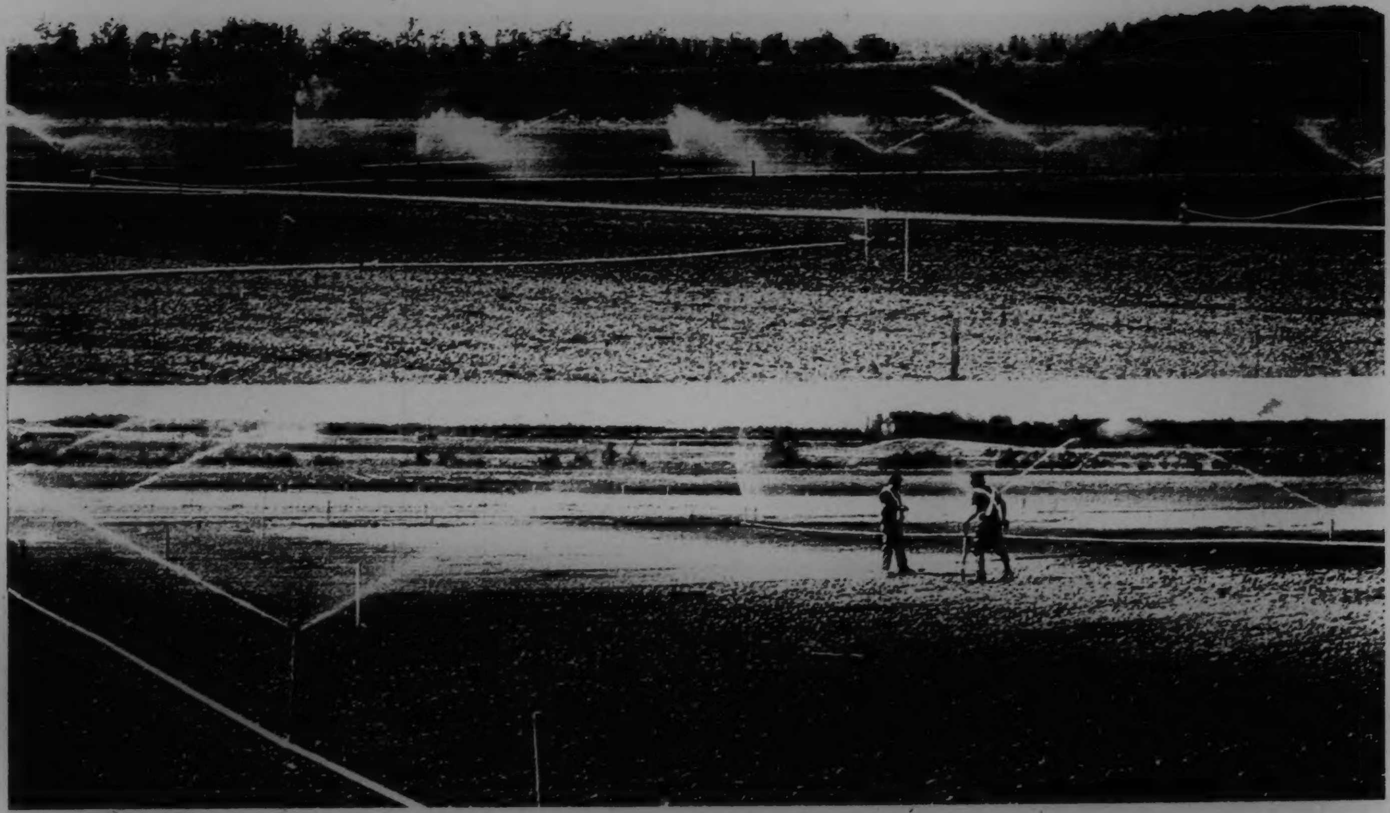

Figure 12.6. Picture shows field site layout top figure was taken looking southwest bottom figure was taken facing northwest (Photos taken: June 15, 2002)

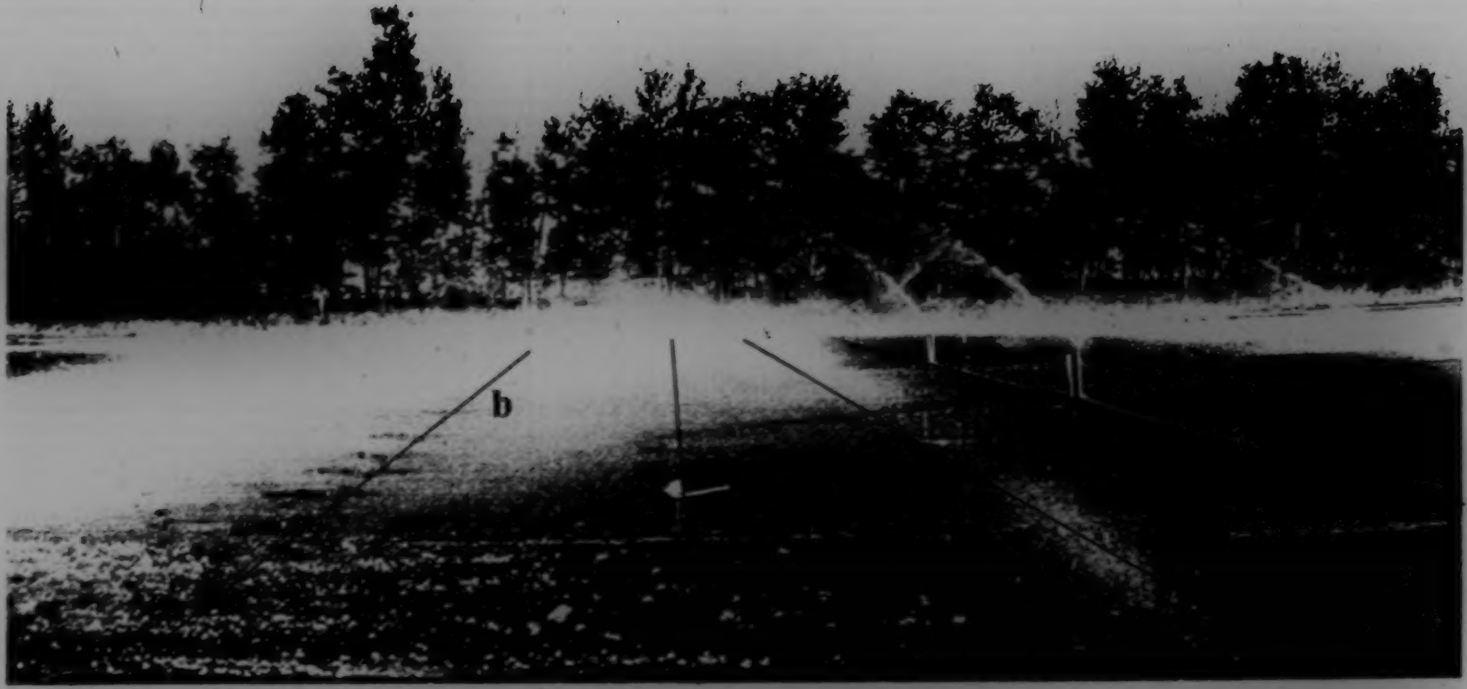

Figure 12.7. Figure shows one of the irrigation treatments and the difference in uniformity of application from the area adjacent to the sprinkler (a) and towards the outer edge of the plot (b) black lines show approximate locations of the hybrid poplar cuttings which were planted within each plot (Photo taken: June 15, 2002)

Figure 12.8. Picture shows example of forage (timothy / alsike clover on left; reed canarygrass / alsike clover in middle; cultivated on right) and cultivated treatments in the northeast block within the field trial (Photos taken: September 4, 2003)

Figure 12.9. Figure shows hybrid poplar planted within one of the irrigation treatments located in the northeast block in both intercropped (left) and cultivated (right) treatments. Figure on left shows locations of both catch cans for assessing application uniformity (a) and access tubes (b) for soil moisture measurements conducted using a neutron probe (Photos taken: September 4, 2003)

13. APPENDIX – F: DATA FROM THE AGRICUTLURAL FEASIBILITY AND IRRIGATION SUITABILITY REPORT (PROUDFOOT, 2000)

Table 13.1. Soil classification of the study site area taken from the Soil Survey of the Tawatinaw Map Sheet (83-I)

Series	%	Soil Group	Dominant Texture	Parent Material	Drainage Class	Topography	Stoniness
Tawatinaw (Tn)	70%	Orthic Gray Luvisol	Loam, sandy loam	Till	well drained	Undulating to moderately rolling	Moderately stony
Codesa Complex (Co)	20%	Degraded Eutric Brunisol and Orthic Gray Luvisol	Sandy loam, loamy sand, occasionally gravelly	12 - 40 inches of alluvial deposits over till	well drained	undulating to gently rolling	Stoneless to slightly stony
Mapova (Mp)	10%	Humic Eluviatd Gleysol	Loam	Till	Poorly drained	Nearly level to gently undulating	Slightly Stony

Kjearsgaard, A.A. 1972. Reconnaissance soil survey of the Tawatinaw map sheet (83-I). Alberta Institute of Pedology. Report No. S-72-29 Canadian Department of Agriculture, Soil Research Institute, University of Alberta.

Table 13.2. Agriculture Feasibility Report for the field study site (NE1/4 17-68-19W4M) conducted by Proudfoot (2000)

<table>
<tr><td>General</td><td colspan="8">This project will irrigate a total of 4.4 acres (1.8 hectares) of hybrid poplar plantations, situated east of the drainage channel on the east edge or NE 17-68-19-W4M. The sprinkler system is specially designed to irrigate a small, rectangular field and apply one half to one inch (1.3 to 2.5 cm) of wastewater per week in one application event per week, depending upon soil and weather moisture conditions. Irrigation water will be applied annually during the May 1 to September 30 growing season period, as needed to supply adequate moisture to crop trees.</td></tr>
<tr><td>Water Supply</td><td colspan="8">The water supply is wastewater effluent produced by the Alberta-Pacific Forest Industries Inc~ pulp mill, and is of suitable quality for irrigation. Water will be conveyed to the area to be irrigated from the nearby pulp mill, either by tanker truck or by buried pipeline.</td></tr>
<tr><td>Soils</td><td colspan="8">A Level II land irrigability classification was completed on July 26, 2000. The entire parcel is rated irrigable, as having <i>good</i> capability (Class 2) for irrigation development. The soils are low in salts and are generally well to rapidly drained Gleyed profiles are found in some low-lying areas but accounts for < 20 % of the soil complex. The gray topsoil is eluviated in addition to having very strongly to medium acid pH of 4.4 to 5.6. Medium to coarse textured, fluvial or eolian sediments are underlain by mainly fine textured, lacustrine and morainal deposits at 100 to 250 cm depths. The surficial, sandy loam or loam to loamy sand textured layer has lower moisture holding capacity but more rapid drainage than the underlying, sandy clay loam or clay loam to clay textured parent materials. Careful irrigation management is required to control the build-up of excessive moisture above the geological contact between the different soil materials.</td></tr>
<tr><td>Topography</td><td colspan="8">The topography has 0.5 to 5 % slopes declining to the west or northwest, suitable to irrigate by sprinkler methods only.</td></tr>
<tr><td rowspan="6">Annual Irrigation Requirements</td><td colspan="6"></td><td>mm</td><td>inches</td></tr>
<tr><td colspan="6">a) Seasonal moisture requirement (young hybrid poplar plantation)</td><td>375</td><td>14.8</td></tr>
<tr><td colspan="6">b) Estimated (growing season) precipitation</td><td>250</td><td>9.8</td></tr>
<tr><td colspan="6">c) Estimated effective stored moisture</td><td>50</td><td>2.0</td></tr>
<tr><td colspan="6">d) Net irrigation requirement</td><td>75</td><td>3.0</td></tr>
<tr><td colspan="6">e) Estimated gross irrigation requirement @ 67% efficiency</td><td>112</td><td>4.4</td></tr>
<tr><td>Method of Irrigation</td><td>Sprinkler system with special design (i.e., hand move)</td><td>Rate of Diversion</td><td>38 litres / second or 501.3 Imperial gallons / minute</td><td>Gross Diversion</td><td>1.6 acre-feet or 1995 m3</td><td>Net Depletion</td><td colspan="2">As for gross diversion</td></tr>
<tr><td>Return Flow</td><td colspan="8">nil</td></tr>
<tr><td>Recommendations</td><td colspan="8">This project is recommended for licensing. Lime or pulp mill sludge applications could increase soil pH towards neutral ant thus enhance the availability of various nutrients, including phosphorus, to out-planted crop trees. Alberta-Pacific Forest Industries, Inc. proposes to conduct long-term research on the site t: 1) Study the economic and silvicultural benefits of irrigating hybrid poplar plantations with pulp mill effluent; as well as 2) monitor environmental effects of wastewater irrigation on quality of local soils and ground water regime.</td></tr>
<tr><td>Prepared by</td><td colspan="2">Robert Proudfoot, P.Ag, R.P.F.</td><td>Company</td><td colspan="2">Soil & Forestry Consulting</td><td>Date</td><td colspan="2">3-Aug-00</td></tr>
</table>

Table 13.3. Agriculture Feasibility Report for the field study site (NE1/4 17-68-19W4M) conducted by Proudfoot (2000) cont'd

Remarks: Classified - 2; S-2; T-2; X, M, L, U

(2) Good Irrigation Capability
(S-2) Irrigable – Good
(T-2) Irrigable – Sprinkler

(X) Moderately to rapidly permeable
(M) Low moisture holding capacity
(L) Geological layering

(U) Earth moving. The land classified within the investigated portion of this quarter section is considered suitable for irrigation development.

Irrigable, good irrigation capability. The Eluviated Dystric Brunisolic soils are low in salts and mainly well to rapidly drained. Gleyed profiles found in some low lying areas show mottled colours in the subsoil, indicative of imperfect drainage and seasonal water logging. The site is situated within the Dry Mixedwood sub-region of Alberta's Boreal Forest natural region. The Brunisolic soils were originally formed under aspen-dominated forest vegetation in a sub-humid climate. These soils, unlike chernozemic soils, have relatively low pH and associated low base saturation throughout the first metre of profile depth. The gray topsoil is eluviated, in addition to having very strongly to medium acid pH of 4.4 to 5.6. Soil reaction increases slightly with depth: 4.6 to 6.0 in the Bm layer and medium to slightly acid pH of 5.2 to 6.2 in the underlying C layer. Acid soils tend to have lower than optimum fertility levels, particularly of plant available nitrogen, phosphorus, potassium, calcium, magnesium and molybdenum.

The soils are formed in medium (sandy loam and loam) to coarse (loamy sand to sand) textured, fluvial or eolian parent materials, underlain by finer, silt loam to silty clay loam or sandy clay loam textured, lacustrine sediments at 100 to 250 cm depths. Fine, clay loam to clay textured, morainal deposits are contacted at 180 to 250 cm depths. The surficial wind- or stream-laid materials are more rapidly drained but have lower moisture holding capacities than underlying lake and glacial materials. Irrigation water applied to supplement rainfall will help improve the available moisture supply for hybrid poplar crop trees, particularly during summer periods of prolonged hot dry weather. Careful irrigation management is required to control the build-up of excessive moisture above the contact between coarse and fine soil parent materials.

Ground water was contacted between 216 and 278-cm depths in water table monitoring wells installed in the north and southern portions of the site.

Topography has 0.5 to 5% slopes declining to the west or northwest, suitable to irrigate by sprinkler methods only

Table 13.4. Characterization of soils for % clay, % sand, % silt, and plant available NO_3, NH_4, PO_4, B, Cu, Fe, Mn, and Zn (mg kg^{-1}) from the field study site conducted by Proudfoot (2000)

Depth (cm)	Horizon	Clay	Sand	Silt	NO_3-N	NH_4-N	PO_4	B	Cu	Fe	Mn	Zn
			%					mg kg^{-1}				
Site #1												
0 - 15	Ap	13	53	34	8.3	0.23	32	0.09	0.5	144	4.9	1
15 - 30	Ae / Bm	15	59	26	7.8	0.23	23	0.07	0.5	164	3.9	0.7
30 - 60	Bm / BC	5.1	92	3.1	0.5	0.16	33.2	0.01	0.5	37.3	0.5	0.3
60 - 100	BC / C	9.1	85	6.1								
100 - 150	C / II-Cgl	10	81	9.1								
Site #2												
0 - 15	Ap	16	44	40	5.6	0.23	28.9	0.11	0.4	49.1	1.3	0.3
15 - 30	Aegj / Bmgj	17	47	36	5.8	0.37	18.4	0.04	0.8	217	4.2	0.7
30 - 60	Bmgj / BCgj	15	68	17	16.9	0.35	12.4	0.13	1.2	107	1.8	0.3
60 - 100	BCgj / Cgj	8.1	88	4								
100 - 150	Cgj / II Cgl	13	76	11								
Site #3												
0 - 15	Ap	12	63	25	4.6	0.32	49.5	0.11	0.4	108	7.4	1.3
15 - 30	Ae / Bm	10	74	16	2.8	0.22	47	0.08	0.8	80.2	2.3	0.7
30 - 60	Bm	12	81	7.2	0.6	0.29	19.6	0.05	0.4	80.3	2.5	0.9
60 - 100	Bm / Btj	15	76	9.1								
100 - 150	Btj / C / II Cgjl	17	71	12								

Table 13.5. Characterization of soils for EC, pH (1:2 soil water), pH (0.01 M $CaCl_2$), sodium adsorption ratio (SAR), soluble Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-, NO_3^- from the characterization of the field study site conducted by Proudfoot (2000) cont'd

	E.C. (1:2)	pH: (1:2)	pH: $CaCl_2$	SAR	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	CO_3^{2-}	HCO_3^-	NO_3^-
	dS m^{-1}	pH			mg kg^{-1}								
Site #1													
0 - 15	0.47	5	4.8	0.4	25.9	2.73	5.2	1.56	5.4	11.2	0.5	16.5	42.9
15 - 30	0.59	4.9	4.7	0.4	25.4	3.23	4.8	1.36	8.4	8.3	0.5	14.8	49.9
30 - 60	0.15	5.5	5	0.8	2.3	0.38	2.4	0.75	2.8	3.3	0.5	9.9	5.97
60 - 100	0.26	5.5	5.2	0.6	5.7	1.49	3.2	0.54					
100 - 150	0.25	5.7	5.4	0.6	5.2	1.3	2.9	0.25					
Site #2													
0 - 15	0.38	4.9	4.6	0.5	17.7	2.12	5.2	0.4	9.5	7.8	0.5	4.9	26.6
15 - 30	0.38	4.8	4.4	0.5	17.3	2.71	5.5	0.82	9.8	8.0	0.5	9.9	25.9
30 - 60	0.25	5.1	4.6	0.8	4.8	1.38	3.9	0.54	4.2	5.3	0.5	12.3	14.6
60 - 100	0.2	5.4	5	0.8	3.6	0.91	3.3	0.52					
100 - 150	0.19	5.6	5.2	0.7	4.0	1.05	3.5	0.3					
Site #3													
0 - 15	0.49	5.6	5.3	0.4	18.5	1.6	3.9	0.87	6.9	6.1	0.5	19.8	36.1
15 - 30	0.42	5.7	5.4	0.4	14.7	1.43	3.5	1.08	3.6	12.6	0.5	19.8	26
30 - 60	0.2	6.1	5.6	0.5	4.7	0.82	2.4	0.48	2.5	4.8	0.5	24.6	8.39
60 - 100	0.2	6.2	6	0.6	4.5	0.87	2.4	0.46					
100 - 150	0.21	6.6	6.2	0.7	4.5	1.07	3.3	0.26					

14. *APPENDIX – G: CLIMATE DATA*

14.1 CALCULATED POTENTIAL EVAPOTRANSPIRATION (PET) AND PRECIPITATION

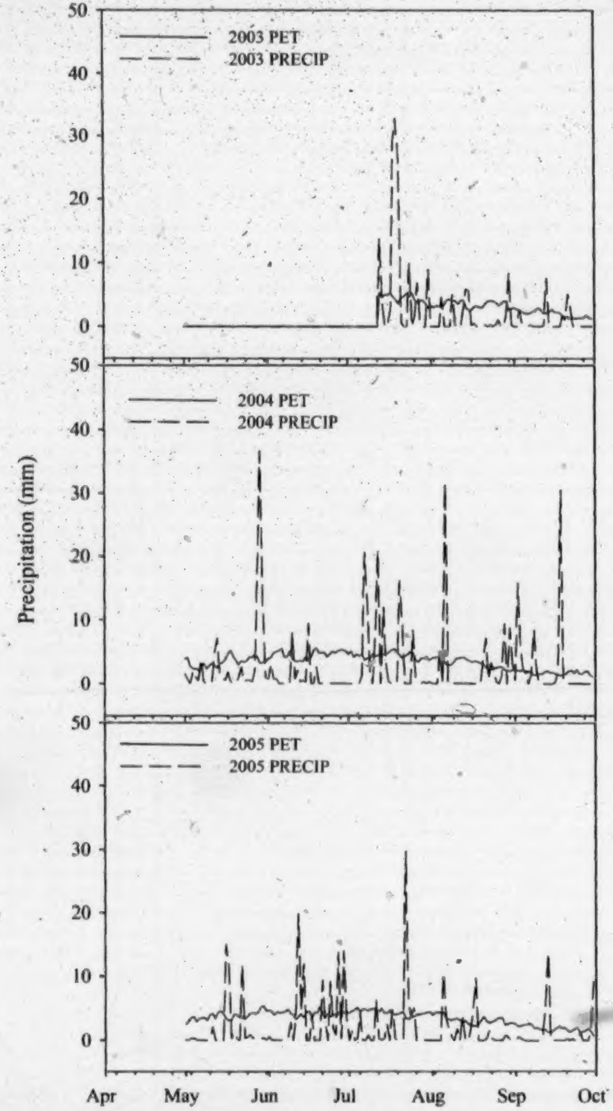

Figure 14.1. Calculated potential evapotranspiration (PET) and actual precipitation (PRECIP) received in 2003, 2004 and 2005

14.2 GROWING SEASON PRECIPITATION

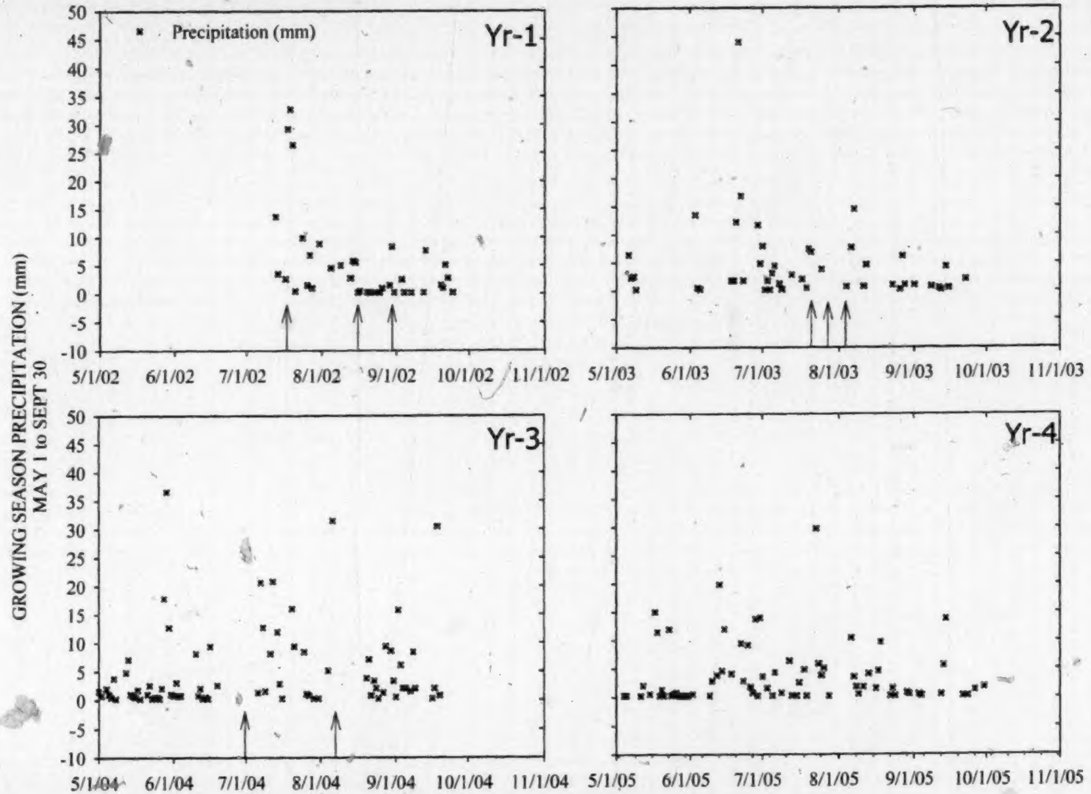

Figure 14.2. Precipitation received during the growing season at the study site from Yr-1 to Yr-4 (Yr-1 = 2002). Arrows show dates on which irrigation events occurred in plots irrigated with either water or KPME.

14.3 GROWING SEASON AIR TEMPERATURE

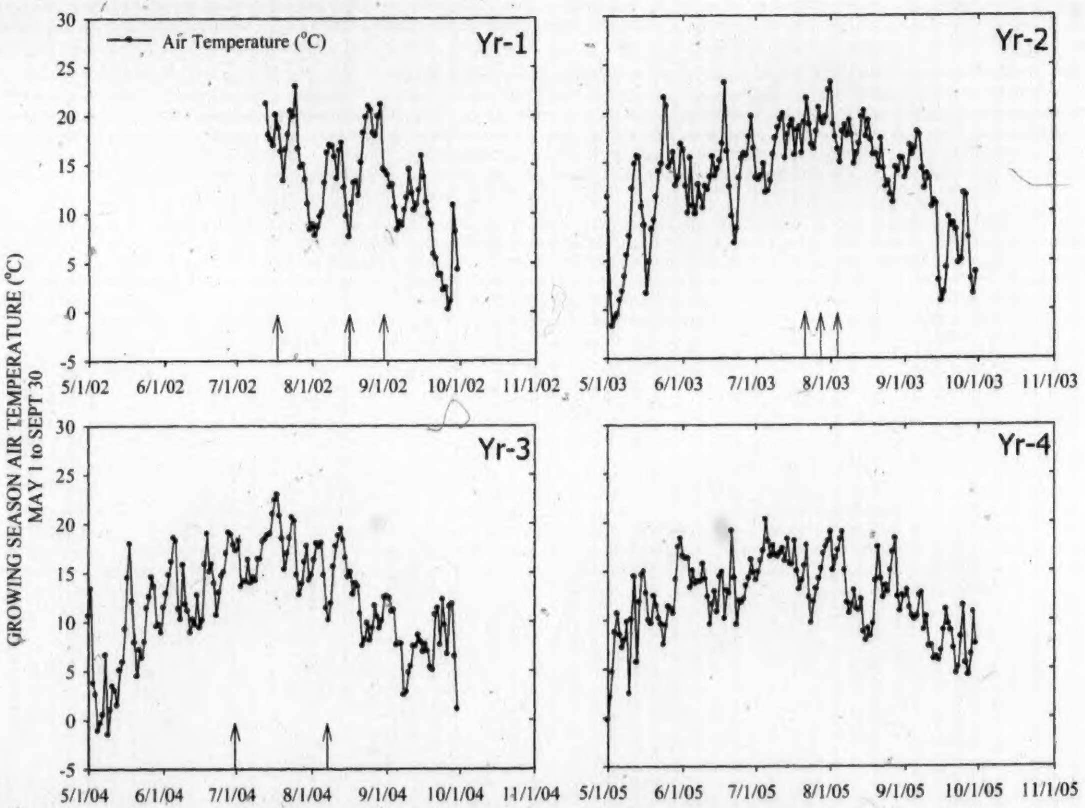

Figure 14.3. Mean air temperature (°C) during the growing season at the study site from Yr-1 to Yr-4 (Yr-1 = 2002). Arrows show dates on which irrigation events occurred in plots irrigated with either water or KPME.

15. *APPENDIX – H: LITERATURE SUMMARY*

Table 15.1. Selected references that involved the use of agricultural, industrial, or municipal effluents for the irrigation of various crop species.

Year	Authors	Title	Information	Effluent types	Crops (Common Name)	Crops (Latin name)	Journal	#	Pages
1980	Hansen, E.A., Dawson, D.H., Tolsted, D.N.	Irrigation of intensively cultured plantations with pulp mill effluent	Pulp mill effluent irrigation of plantations	Pulp mill	Willow; Poplar	*Salix; Populus*	Tappi	63 (11)	139-143
1982	Tesar, M.B., Knezek, B.D.	Management studies of annual grasses and perennial legumes and grasses at the Michigan State University water quality management facility.	Effect of municipal effluent on forage and annual crop production	Municipal	Smooth brome; Orchardgrass; Tall fescue; Timothy; Kentucky Bluegrass; Creeping foxtail; Reed canarygrass; Alfalfa; Birdsfoot trefoil; Corn; Sorghum-sudangrass; Sorghum	*Bromis inermis; Dactylis glomerata; Festuca arundinacea; Phleum pratense; Poa pratensis; Alopecurus arudinaceus; Phalaris arundinacea; Medicago sativa; Lotus cornicalatus; Zea mays; Sorghum bicolor*	in F. M. D'Itri ed. Land treatment of municipal wastewater – Vegetation selection and management		79-105

Table 15.1 cont'd. Selected references that involved the use of agricultural, industrial, or municipal effluents for the irrigation of various crop species

Year	Authors	Title	Information	Effluent types	Crops (Common Name)	Crops (Latin name)	Journal	#	Pages
1984	Linden, D.R., Clapp, C.E., Larson, W.E.	Quality of percolate water after treatment of a municipal effluent by a crop irrigation system	Crop management under effluent irrigation and the impacts on percolate water	Municipal effluent	Corn; Reed Canarygrass	*Zea mays; Phalaris arundinacea*	J. Environ. Qual.	13 (2)	256-264
1990	Hayes, A.R., Mancino, C.F., Pepper, I.L.	Irrigation of turfgrass with secondary sewage effluent: I. Soil and leachate water quality	Effect of sewage sludge irrigation on leachate water quality	Secondary Municipal Effluent	Bermudagrass	*Cynodon dactylon*	Agron. J.	82	939-943
1990	Kannan, K., Oblisami, G.	Influence of irrigation with pulp and paper mill effluent on soil chemical and microbiological properties	Effect of pulp and paper mill effluents on soil chemistry	Pulp mill; Paper mill	Sugarcane		Biol. Fertil. Soils	10	197-201
1991	Chauhan, C.P.S., Singh, R.B., Minhas, P.S., Agnihotri, A.K., Gupta, R.K.	Response of wheat to irrigation with saline water varying in anionic constituents and phosphorus application	Irrigation of wheat with saline water of varying ionic concentrations	Saline Water	Wheat	*Triticum aestivum*	Agric. Water Manage.	20	223-231
1992	Mancino, C.F., Pepper, I.L.	Irrigation of turfgrass with secondary sewage effluent: Soil Quality	Effect of sewage sludge irrigation on soil quality	Secondary Municipal Effluent	Bermudagrass	*Cynodon dactylon*	Agron. J.	84	650-654

Table 15.1 cont'd. Selected references that involved the use of agricultural, industrial, or municipal effluents for the irrigation of various crop species

Year	Authors	Title	Information	Effluent types	Crops (Common Name)	Crops (Latin name)	Journal	#	Pages
1992	Bajwa, M.S., Choudhary, O.P., Josan, A.S.	Effect of continuous irrigation with sodic and saline-sodic waters on soil properties and crop yields under cotton-wheat rotation in northwestern India	Cyclic irrigation with sodic and saline-sodic waters on cotton-wheat rotation	sodic; saline-sodic; water	Cotton; Wheat	*Gossypium; Triticum aestivum*	Agric. Water Manage.	22	345-356
1992	Carlson, M.	Municipal effluent irrigation of fast growing hybrid poplar plantations near Vernon, British Columbia			Poplar	*Populus*	For. Chron.	68 (2)	206-208
1993	Bajwa, M.S., Josan, A.S., Choudhary, O.P.	Effect of frequency of sodic and saline-sodic irrigations and gypsum on the buildup of sodium in soil and crop yields	Impact of saline-sodic and sodic water and gypsum applications on crop yields and soil chemistry	Saline-sodic; sodic water	Millet; Wheat; Maize	*Pennistem typhoids; Triticum aestivum; Zea mays*	Irrig. Sci	14	21-26

Table 15.1 cont'd. Selected references that involved the use of agricultural, industrial, or municipal effluents for the irrigation of various crop species

Year	Authors	Title	Information	Effluent types	Crops (Common Name)	Crops (Latin name)	Journal	#	Pages
1993	Minhas, P.S., Gupta, R.K.	Conjunctive use of saline and non-saline waters. I. Response of wheat to initial salinity profiles and salinization patterns	Cyclic irrigation with saline and non-saline water on wheat	Saline Water; Non-saline water	Wheat	*Triticum aestivum*	Agric. Water Manage.	23	125-137
1999	Howe, J., Wagner, M.	Effects of pulp mill effluent irrigation on the distribution of elements in the profile of an arid region soil	Distribution of elements 15 yrs after irrigation was stopped	Pulp mill	Saltbrush	*Atriplex canescens*	Environ. Pollut.	105	129-135
1999	Bañuelos, G.S., M.C. Shannon, H. Ajwa, J.H. Draper, J. Jordahl, and L. Licht.	Phytoextraction and accumulation of boron and selenium by poplar (*Populus*) hybrid clones			Poplar	*Populus*	Inter. J. Phytoremed	1 (1)	81-96
2000	Huang, Z.B., Assouline, S., Zilberman, J., Ben-Hur, M.	Tillage and saline irrigation effects on water and salt distribution in a sloping field	Effect of saline irrigation water on crop yield and salt distribution	Saline water	Corn	*Zea mays*	Soil Sci. Soc. Am. J.	64	2096-2102

Table 15.1 cont'd. Selected references that involved the use of agricultural, industrial, or municipal effluents for the irrigation of various crop species

Year	Authors	Title	Information	Effluent types	Crops (Common Name)	Crops (Latin name)	Journal	#	Pages
2000	Sakadevan, K., Maheshwari, B.L., Bavor, H.J.	Availability of nitrogen and phosphorus under recycled water irrigation	N and P loadings of effluent irrigation	Recycled water	Ryegrass; White clover	*Lolium perenne; Trifolium repens*	Aust. J. Soil Res.	38	653-664
2001	Qadir, M., Ghafoor, A., Murtaza, G.	Use of saline-sodic waters through photoremediation of calcareous saline-sodic soils	Use of alternative waters for irrigation in arid and semiarid regions	Drainage Water	Rice; Wheat	*Oryza sativa; Triticum aestivum*	Agric. Water Manage.	50	197-210
2001	Shani, U., Dudley, L.M.	Field studies of crop response to water and salt stress	Crop responses to water and salt stress; Deficit irrigation		Corn, melon, alfalfa	*Zea mays; Cucumis melo; Medicago sativa*	Soil Sci. Soc. Am. J.	65	1522-1528
2002	Bañuelos, G.S.	Irrigation of broccoli and canola with boron- and selenium-laden effluent	Effect of drainage effluent on soil chemistry	Drainage Water	Canola; Broccoli	*Brassica napus; Brassica oleracea*	J. Environ. Qual.	31	1802-1808
2002	Buckland, G.D., Bennett, D.R., Mikalson, D.E., de Jong, E., Chang, C.	Soil salinization and sodification from alternate irrigations with saline-sodic water and simulated rain	Soil salinity and sodicity	Saline-sodic water; rain water	White spring wheat	*Triticum aestivum*	Can. J. Soil Sci.	82	297-309

Table 15.1 cont'd. Selected references that involved the use of agricultural, industrial, or municipal effluents for the irrigation of various crop species

Year	Authors	Title	Information	Effluent types	Crops (Common Name)	Crops (Latin name)	Journal	#	Pages
2003	Mohammad, M.J., Mazahreh, N.	Changes in soil fertility parameters in response to irrigation of forage crops with secondary treated wastewater			Corn; Vetch	*Zea mays; Vicia sativa*	Commun. Soil Sci. Plant Anal.	34 (9-10)	1281-1294
2004	Bolan, N.S., Home, D.J., Currie, L.D.	Growth and chemical composition of legume-based pasture irrigated with dairy effluent	Dairy effluent irrigation	Dairy effluent	Perennial rye grass; white clover	*Lolium perenne; Trifolium repens*	New Zeal. J. Agric. Res.	47	85-93
2004	Grattan, S.R., Grieve, C.M., Poss, J.A., Robinson, P.H., Suarez, D.L., Benes, S.E.	Evaluation of salt-tolerant forages for sequential water reuse systems III. Potential implications for ruminant mineral nutrition	Impacts of effluent irrigation on ruminant mineral nutrition	Drainage Water	Alfalfa; Narrowleaf trefoil; Broadleaf trefoil; Tall Wheatgrass; Alkali sacaton; Kikuyugrass; Paspalum; Bermudagrass	*Medicago sativa; Lotus glaber; L. ulginosus; Agropyron elogatum; Sporobolus airoides; Pennisetum clandestinum; Paspalum vaginatum; Cynodon dactylon*	Agric. Water Manage.	70	137-150

Table 15.1cont'd. Selected references that involved the use of agricultural, industrial, or municipal effluents for the irrigation of various crop species

Year	Authors	Title	Information	Effluent types	Crops (Common Name)	Crops (Latin name)	Journal	#	Pages
2004	Grieve, C.M., Poss, J.A., Grattan, S.R., Suarez, D.L., Benes, S.E., Robinson, P.H.	Evaluation of salt-tolerant forages for sequential water reuse systems II. Plant-ion relations	Salt tolerance in plants for use in recycled water systems	Drainage Water	Alfalfa; Narrowleaf trefoil; Broadleaf trefoil; Tall Wheatgrass; Alkali sacaton; Kikuyugrass; Paspalum; Bermudagrass	*Medicao sativa; Lotus glaber; L. ulginosus; Agropyron elogatum; Sporobolus airoides; Pennisetum clandestinum; Paspalum vaginatum; Cynodon dactylon*	Agric. Water Manage.	70	121-135
2004	Mishra, A., Sharma, S.D., Pandey, R.	Amelioration of degraded sodic soil by afforestation	Afforestation effects on sodic soils		Mesquite; Shisham; Forest Red Gum	*Prosopis juliflora; Dalbergia sissoo; Eucalyptus tereticornis*	Arid Land Res. Manage.	18	13-23
2004	Mohammad, M.J., Ayadi, M.	Forage yield and nutrient uptake as influenced by secondary treated wastewater	Nutrient uptake and crop yield after irrigation with secondary municipal effluent	Municipal	Corn; Vetch	*Zea mays; Vicia sativa*	J. Plant Nut.	27 (2)	351-365

Table 15.1cont'd. Selected references that involved the use of agricultural, industrial, or municipal effluents for the irrigation of various crop species

Year	Authors	Title	Information	Effluent types	Crops (Common Name)	Crops (Latin name)	Journal	#	Pages
2005	Aydemir, S., Najjar, N.F., Hallmark, C.T.	Exchangeable sodium accumulation with irrigation in soils under turfgrass	Na accumulation under sodic water irrigation	Sodic water	Bermudagrass; St. Augustine grass	*Cynodon dactylon; Stenotaphrum secundatum*	Commun. Soil Sci. Plant Anal.	36	1611-1624
2005	Baumgartner, D.J., Glenn, E.P., Thompson, T.L., Skeen, B.A.	Land disposal of concentrate from biosolids production	Irrigation of arid land and riparian plants	Municipal	Cattail; Reed; Cottonwood; Saltcedar; Fourwing saltbrush; Cotton	*Typha domingensis; Arundo donax; Populus fremontii; Tamarix ramosissima; Atriplex canescens; Gossypium hirsutum*	Water, Air, and Soil Pollut.	162	219-228
2005	Kaushik, A., Nisha, R., Jagjeeta, K., Kaushik, C.P.	Impact of long and short term irrigation of a sodic soil with distillery effluent in combination with bioamendments	Effluent irrigation and soil amendments	Distillery effluent	Pearl millet	*Pennisetum glaucum*	Biores. Tech.	96	1860-1866

16. *APPENDIX – I: ABSTRACTS FOR MANUSCRIPTS*

16.1 CHAPTERS SUBMITTED FOR PUBLICATION

16.1.1 Chapter 2: Effect of Municipal and Pulp Mill effluents on the Chemical Properties and Nutrient Status of a Coarse Textured Brunisol in a Growth Chamber

S. J. Patterson*, D. S. Chanasyk, M. A. Naeth, and, E. Mapfumo

Department of Renewable Resources, University of Alberta, 751 GSB, Edmonton, AB, Canada, T6G 2H1.

**Corresponding Author (pattsj@telusplanet.net). Received:*________________.

Maximizing productive use and minimizing the environmental impacts of effluents require research on application rates. This study evaluated the effect of effluents from a Kraft pulp mill [a final effluent (KPME) and a waste activated sludge (WAS)], a municipal effluent (ME) and tap water (TPW) applied at rates of 1.5, 3, and 6 mm d^{-1} on reed canarygrass (*Phalaris arundinacea* L. cv. Vantage) and hybrid poplar (*Populus deltoides* x *P. petrowskyana* var. Walker). The two pulp mill effluents significantly increased soluble soil Na^+, SO_4^{2-}, and Cl^-. Soil solution EC and SAR increased with pulp mill effluents compared to ME and TPW. Soil solution SAR increased from less than 1 to a range of 2.7 to 4.0 for the municipal effluent and 8.4 to 14.0 for the two pulp mill effluents. ECe increased from 1.1 to 2.3 dS m^{-1} to a range of 1.8 to 3.4 dS m^{-1} for municipal effluent and 5.1 to 6.1 dS m^{-1} because of pulp mill effluent applications. Under reed canarygrass, soils had lower concentrations of cations and anions than those under hybrid poplar, suggesting crop uptake and leaching. Thus, soil salt loading must be considered when determining application rates of effluents.

Key words: hybrid poplar, effluent irrigation, SAR, EC

Abbreviations: EC, electrical conductivity; ET, evapotranspiration; KPME, Kraft pulp mill effluent; ME, municipal effluent; SAR sodium adsorption ratio; TPW, City of Edmonton tap water; WAS, waste activated sludge

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16.1.2 Chapter 3: Effluent Effects on a Coarse Textured Soil and Associated Impacts on the Nutrient Concentrations and Growth of Reed Canarygrass (Phalaris arundinacea L.) and Hybrid Poplar (Populus deltoides x P. petrowskyana L.)

S. J. Patterson*, D. S. Chanasyk, M. A. Naeth, and E. Mapfumo

Department of Renewable Resources, University of Alberta, Room 751 GSB, Edmonton, AB, Canada, T6G 2H1. *Corresponding Author (pattsj@telusplanet.net). Received:________________.

Using effluent as a source of irrigation water is gaining favor as an environmentally positive practice, as effluents can provide suitable sources of water and nutrients for plant growth. A growth chamber study was conducted to evaluate the effects of water (TPW), municipal effluent (ME), and Kraft pulp mill effluent (KPME) and waste activated sludge (WAS) at rates of 1.5, 3, and 6 mm d^{-1} had on available soil nutrients, nutrient uptake, and growth of reed canarygrass (RCG; *Phalaris arundinacea* L.) and hybrid poplar (HYPB; *Populus deltoides* x *P. petrowskyana* L.). Increasing the application rate significantly increased biomass for both crops, but the KPME treatment significantly decreased leaf area of the HYBP. Effluent applications did not result in toxic accumulations of nutrients within the analyzed tissues for either RCG or HYBP. Only the WAS treatment significantly increased soil available concentrations of P, K, S, B, Mn, and Zn.

Key words: effluent irrigation, hybrid poplar, nutrient concentration, reed canarygrass

Abbreviations: EC, electrical conductivity; ET, evapotranspiration; KPME, Kraft pulp mill effluent; ME, municipal effluent; SAR sodium adsorption ratio; TPW, City of Edmonton tap water; WAS, waste activated sludge

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16.1.3 Chapter 4: Effects of Diluted Kraft pulp Mill Effluent on Hybrid Poplar and Soil Chemical Properties

S.J. Patterson*, D.S. Chanasyk, E. Mapfumo, and M.A. Naeth

Department of Renewable Resources, University of Alberta, 751GSB, Edmonton, AB, Canada, T6G 2H1.

**Corresponding Author (pattsj@telusplanet.net). Received:_________________.*

Irrigation with effluents can detrimentally affect soil physical and chemical properties and impact plant growth and development. Excessive irrigation can leach salts from the root zone; which can be accomplished by precipitation in some areas. This study was conducted to examine the effect of applications of Kraft pulp mill effluent (KPME) with and without distilled water (DW) to simulate precipitation would have on soil chemical properties and growth of hybrid poplar (*Populus deltoides x P. petrowskyana* L. cv. Walker). Distilled water (DW), KPME, and a 50% combination (v/v; COMB) of DW and KPME were applied at rates of 6 and 9 mm d^{-1}. COMB resulted in heights, biomasses, and leaf areas that were greater than those for KPME and comparable to those for DW. Diluted KPME treatments (i.e., COMB) still significantly increased soil electrical conductivity and sodium adsorption ratio compared to DW. Leachate collected from KPME 9 mm d^{-1} had concentrations of HCO_3^-, SO_4^{2-}, Cl^-, Ca^{2+}, K^+, and Mg^{2+} comparable to those collected from COMB 9 mm d^{-1}, but Na^+ concentrations were 3 times higher in KPME than COMB 9 mm d^{-1}. Results indicate that precipitation or additional irrigation water could potentially provide the leaching necessary to prevent salt accumulation within the rooting zone; however, irrigating with saline or sodic effluents requires careful management.

Key words: effluent irrigation, hybrid poplar, effluent irrigation, electrical conductivity, gypsum, sodium adsorption ratio

Abbreviations: EC, electrical conductivity; ET, evapotranspiration; KPME, Kraft pulp mill effluent; SAR sodium adsorption ratio; WAS, waste activated sludge, COMB combination treatment

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16.2 CHAPTERS TO BE SUBMITTED

16.2.1 Chapter 5: Growth of Winter Wheat Irrigated With Diluted Kraft Pulp Mill Effluent on Soils Amended With Gypsum and Wood Ash

S.J. Patterson[1*], D. S. Chanasyk[1], and V. S. Baron[2]

[1]Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada, T6G 2H1,
[2]Research Centre, Agriculture and Agri-Food Canada, Lacombe Alberta, Canada, T4L 1W1,
**Corresponding author (pattsj@telusplanet.net)*

Supplementing irrigation water with effluents could reduce the need for potable water for irrigation and promote nutrient recycling, but may require additional amendments to deal with Na. Winter wheat was seeded into a control soil and to soil amended with either gypsum or wood ash applied at an equivalent rate of 15 dry t ha^{-1}. Wheat was irrigated at a rate of 6 mm d^{-1} with distilled water (DW), Kraft pulp mill effluent (KPME) and waste activated sludge (WAS), and three KPME/WAS combinations. This included two KPME/WAS combinations diluted with DW to 25 and 50% (KPME/WAS:DW) to evaluate the effect on the nutrient uptake and biomass and the impact on soluble ions in the soil. Effluent applications increased wheat biomass and these increases were greater in soils containing ash and gypsum-amendments than control soils. Effluent applications increased soil pH, soluble Na^+, Ca^{2+}, SO_4^{2-}, and Cl^-, but only the gypsum reduced sodium adsorption ratio (SAR) in all soils except those applied with WAS. Effluent combinations at the lower dilutions in combination with gypsum could be used to provide supplemental water with moderate increases in electrical conductivity (ECe) and SAR that would still be within tolerable limits of many crops.

Key words: amendments, hybrid poplar, effluent irrigation, electrical conductivity, gypsum, sodium adsorption ratio, wood ash

Abbreviations: DW, distilled water; ECe, electrical conductivity; ET, evapotranspiration; KPME, Kraft pulp mill effluent; ME, municipal effluent; SAR sodium adsorption ratio; WAS, waste activated sludge

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16.2.2 Chapter 6: Irrigating Soil with Kraft Pulp Mill Effluent Under Field Conditions

S.J. Patterson*, D.S. Chanasyk, V.S. Baron, M.A. Naeth, E. Mapfumo, S.X. Chang, C. Kaiser, E. Dzus, and A.M. Jobson

Department of Renewable Resources, University of Alberta, 751GSB, Edmonton, AB, Canada, T6G 2H1.

**Corresponding Author (pattsj@telusplanet.net). Received:__________________.*

Effluent irrigation provides a supplemental source of water for sub-humid regions where water limitations are often experienced by plants. While salts can potentially limit the degree to which effluents are used for irrigation, in some areas, precipitation can leach salts from the root zone instead of excessive irrigation, as is a common practice in some irrigated areas. A five-year field study evaluated the effect of effluent irrigation on the chemical properties of soil planted with either hybrid poplar (*Populus deltoides* x *P. petrowskyana* L. cv. Walker) or poplar intercropped with timothy (*Phleum pratense* L. cv. Climax) and alsike clover (*Trifolium hybridum* L. cv. Aurora). Three years of Kraft pulp mill effluent (KPME) applications at rates of 3 mm d^{-1} were followed by two years of no irrigation. KPME applications significantly increased soil soluble Na^+, Ca^{2+}, SO_4^{2-}, Cl^-, EC, and SAR, in saturated paste extracts. The vegetative cover reduced soluble Ca^{2+}, Na^+, Mg^{2+}, and solution EC, but increased SAR. Precipitation reduced salt accumulation within the rooting zone. However, more research is required re the management and timing of applications as effluent applications are likely required only during dry periods.

Key words: agroforestry, hybrid poplar, effluent irrigation, electrical conductivity, sodium adsorption ratio

Abbreviations: ECe, electrical conductivity; ET, evapotranspiration; KPME, Kraft pulp mill effluent; SAR, sodium adsorption ratio

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